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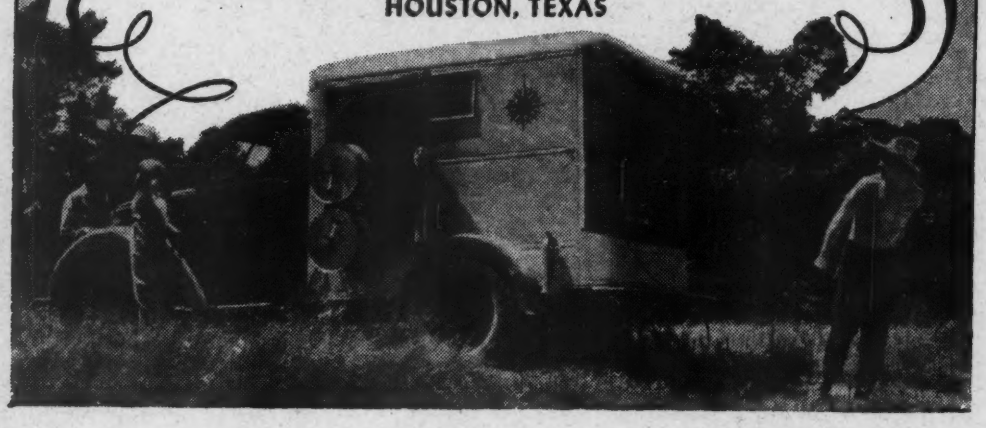


VOLUME X JANUARY, 1945 NUMBER 1

GEOPHYSICS

A Journal of General and Applied Geophysics

HISTORY OF THE GEOPHYSICAL EXPLORATION OF THE CAMERON MEADOWS DOME, CAMERON PARISH, LOUISIANA*

GLENN M. McGUCKIN†

ABSTRACT

In order to demonstrate the growth of our knowledge of a typical Gulf Coast salt dome concurrently with development of the science of geophysics, the successive application of various techniques to the exploration of the Cameron Meadows dome is described and illustrated. These methods were: mechanical refraction seismograph (1926); torsion balance (1927); electrical refraction seismograph (1928–29); early correlation reflection seismograph (1929); dip reflection seismograph (1933); special salt profiling refraction seismograph (1942); continuous correlation reflection seismograph (1942); gravity meter (1943.)

INTRODUCTION

This paper is intended to show the growth of our knowledge of a typical Gulf Coast salt dome, as the science of geophysics developed, by the successive application to the area including the dome of the various methods of geophysical exploration.

The discovery well of the Cameron Meadows field, Cameron Meadows Land Company No. 1, was completed in January, 1931, as a gasser and the field has produced 10,800,000 barrels of oil to January 1, 1944. The first indication of a possible oil source was a line of gas seepages known to trappers. The successive stages in geophysical exploration were:

1. Seismos Company mechanical refraction seismograph for a group composed of Calcasieu Oil Company, Union Sulphur Company, and Magnolia Petroleum Company, 1926.
2. Vacuum Oil Company torsion balance, 1927.
3. Geophysical Research Corporation for Vacuum Oil Company.
   a. Refraction seismograph survey—early 1928
   b. Refraction seismograph survey and
   c. Correlation reflection seismograph } 1929

* Presented at the fourteenth annual meeting, Dallas, Texas, March 1944.

† Magnolia Petroleum Company, Dallas, Texas.

4. Geophysical Service, Inc., dip reflection seismograph, 1933, for Magnolia Petroleum Company.

5. McCollum Exploration Company refraction seismograph survey by means of detectors in an abandoned flank test, 1942, for Magnolia Petroleum Company and Humble Oil and Refining Company.

6. Petty Geophysical Engineering Company reflection seismograph, 1942, for Magnolia Petroleum Company and Humble Oil and Refining Company.

7. Robert H. Ray, Inc., gravity meter regional survey for Yegua Corporation, 1943.

References in the literature to the Cameron Meadows dome are the two following:

1. "The Cameron Meadows dome was intimated by gas seeps known to trappers in the marshes covering this area. These seeps were brought to (Henry C.) Cortes' attention in March, 1926. At the opportune time, leases on more than 18,000 acres were taken by the Vacuum (now the Magnolia Petroleum Company) and geophysical work commenced. A significant (torsion balance) gravity minimum indicating deep salt was found which was later confirmed by both refraction and reflection seismograph work."—L. P. Teas, A.A.P.G. Bull., Vol. 16, p. 255, March, 1932.

2. "The dome lies entirely within the area of the Cameron marsh and it has no recognizable physiographic expression from airplane photographs." "Old North Bayou pursues a meandering course across the marsh and may possibly be deflected slightly to the northwest in the immediate area of the dome."—Louisiana Geological Bull. #6, November 1, 1935, p. 138. Fig. 1 portrays the surface conditions, with the location of the gas seeps shown by solid stars.

The gas seepages above referred to were known as "boils," being several inches in diameter. They were stronger in volume than the ones leading to the Lockport field discovery, Calcasieu Parish, Louisiana. Due to their amount and constancy over a number of years this was indicative of a petroleum source. A further point of interest is the fact that the seepages about the northeast corner of Section 28 are sulphur gas, whereas those to the east in Section 27 contain no sulphur gas.

The surface of this area is covered by shallow water and marsh grass throughout most of the year, so the various surveys were made by means of boat and pack equipment and later included marsh buggies.

PRODUCTION

The first test on this dome was Vacuum Oil Company, Cameron Meadows #1. After a number of shows from 1000 feet on down, it blew out at 3814 feet, and would have been completed as an oil well at

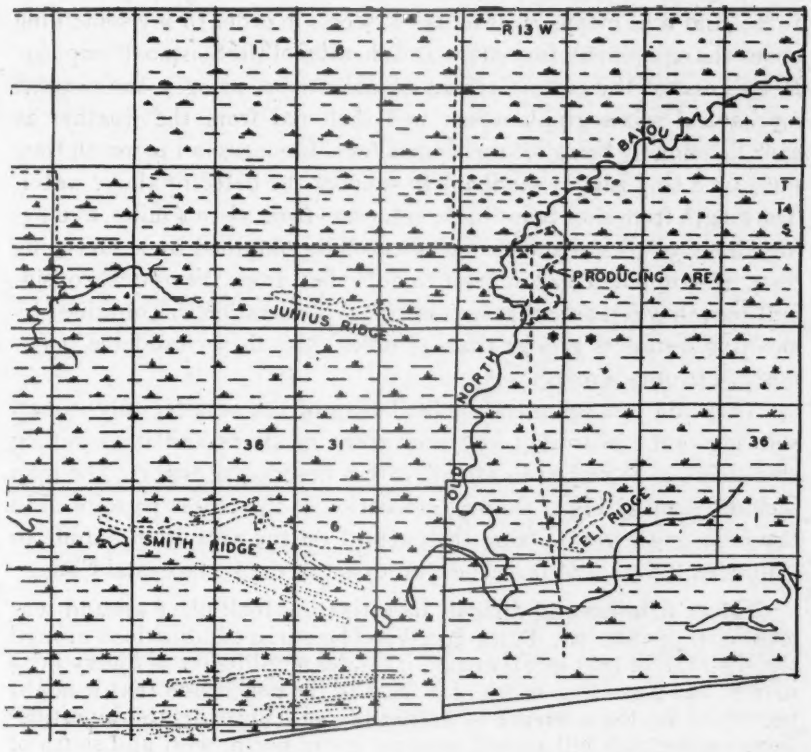


FIG. 1. Topographic map of Cameron Meadows. From U.S.G.S., Cameron Parish, La. Location of gas seeps shown by solid stars.

5248 feet but for mechanical difficulties. It was sidetracked and completed in January 1931, at 3850 feet, making 50,000 cubic feet of gas and a spray of oil.

Production of the field to January 1, 1944, amounted to 10,800,000 barrels of oil, producing from Pliocene and upper Miocene sands from 1300 feet to 5685 feet depth.

GEOPHYSICAL EXPLORATION

1. In 1926 Calcasieu Oil Company, for the account of Union Sulphur Company, Magnolia Petroleum Company and themselves, em-

ployed the Seismos Company to make seismograph surveys of large coastal areas, including Cameron Meadows. The work, particularly on Cameron Meadows, extended from March to August of the above year.

For the sake of those who have entered the field of geophysics since 1926—and that means most of us—it seems in order to say something about the equipment, procedure, and theories of the Seismos Company. It was one of the early German organizations, using a one-channel mechanical seismograph which was sheltered from the weather at each location by being set up inside a tent. In places in the marsh they built up a tiny islet of sandbags to support the detector above water. The length from shot point to detector was from 1½ to 4 miles, averaging about 3 miles, distances being carefully obtained by a surveying crew. It is of particular interest to note that, from theoretical considerations, they felt sure that no additional penetration was obtained by shooting distances greater than 3½ miles. Also they considered it impossible to obtain reflections.

They did not submit a detailed map of the results; only a map showing tent (recording) and shot point locations and lines joining shot point to recording locations, with a descriptive report. The map included here as Fig. 2 shows the location of the points mentioned in the following excerpts from their report on the area from Sabine to Calcasieu Rivers, and from the Gulf Coast to the Intracoastal Canal:

"More detailed and difficult investigation took place around tent location 145 (Sec. 21, T14S, R13W). The surface indications around the shell hill of tent location 145, its sudden uplift out of a very deep marsh, and a gas seep south of it, lead to the conclusion that it might be caused by the presence of harder layers. However, the investigations on the shell hill as well as those going north, west and south of it show clearly that no harder layers occur down to considerable depths. The first under-layer was stated in a depth of 1600 feet near shot 161, while it is of 1900 feet near shot 160."

In the conclusions to their report, however, they say:

"The region around the shell hill in T14S, R13W, tent location 145, cannot be called fully normal; there may be a possibility to find a structure in Sections 21 and 28 of this region."

In his letter transmitting the Seismos report, Mr. Harry C. Hanszen of Calcasieu Oil Company said, "I feel that outside of" (certain small areas) "mentioned in Dr. Rellensmann's report, the entire area has been thoroughly covered, and when the special work recommended

by Dr. Rellensmann is completed" (for these small areas) "this vast body of land will have been thoroughly tested out with the seismograph." Following the subsequent special work above mentioned, he said, "Briefly, nothing very unusual was found in this special work except a fault in the neighborhood of Shell Hill, just east of Junius

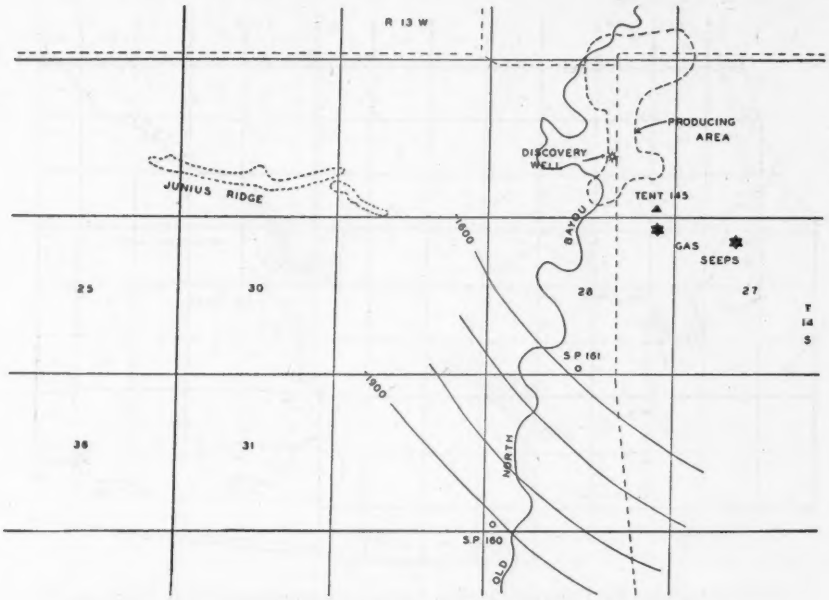


FIG. 2. Seismos Company dip indication map, 1926, Cameron Meadows, Cameron Parish, La. Gas seeps shown by solid stars, recording station ("tent") by solid triangle, shot points by open circles. Contour interval is 100 feet.

Ridge, Sections 21 and 28." This is in the vicinity of the Cameron Meadows Dome.

2. A Vacuum Oil Company crew made a reconnaissance torsion balance gravity survey in 1927, the results of which are shown in Fig. 3. Station locations were made principally from boats along the banks of streams, canals and lakes. The results indicated a large closed minimum anomaly with the gas seepage area on the east nose. One well, Humble Oil and Refining Company-Magnolia Petroleum Company #B1 Cameron Meadows Land Company, in Section 24, T14S, R13W, 3 miles west of the discovery well, was drilled on the basis of torsion balance results to 6824 feet and abandoned, with no oil, gas or other

favorable indications. The torsion balance survey work was never completed in detail.

3. The first electrical seismograph work was done for Vacuum Oil Company by Geophysical Research Corporation. Their exploration was done in three stages:

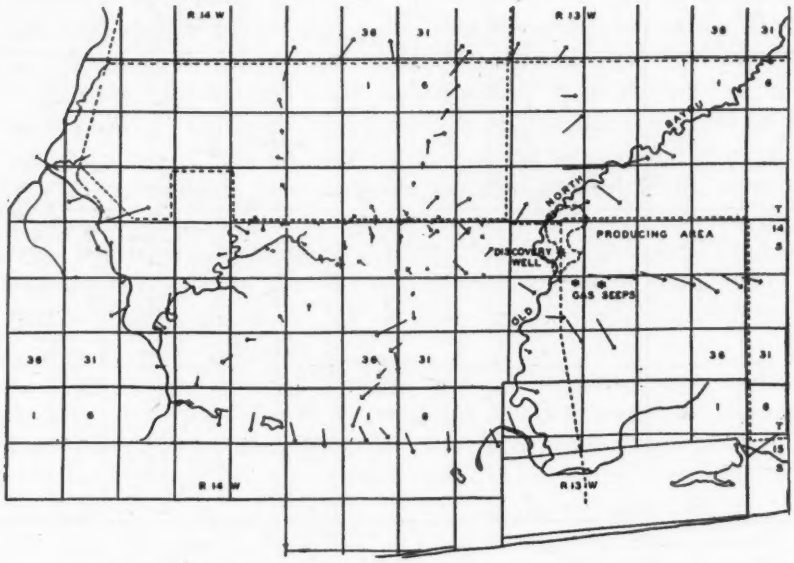


FIG. 3. Vacuum Oil Company torsion balance reconnaissance map, 1927, showing observed gravity gradients. Dashed line about discovery well encloses producing area. Other dashed lines are canals.

a. A preliminary refraction seismograph survey consisting of fans was made in an effort to find a salt dome under or near the gas seepages. The first fan was from shot point #9, Fig. 4, in January 1928, by Dr. H. B. Peacock. He interpreted the time values obtained from this fan as strongly indicative of a salt dome, in Section 27, T14S, R13W. The next work was a fan from shot point #78 by Mr. K. E. Burg. The detectors for this last fan were so close to the north side of the dome that the mirage distance fell somewhere about the south side of the dome. Consequently their supervisory staff reviewed the data from all these shots and concluded no salt dome existed in the area. Dr. Peacock, in his report on the later shooting, agreed with them that "previously secured leads [from shot point #9] are entirely due to a fairly high speed layer not normally encountered in this area."

It was following this that the Geophysical Research Corporation adopted the now conventional graphical method of plotting the fan time leads on radii extending out from the shot point towards the respective detectors. After plotting the data in that manner, the area

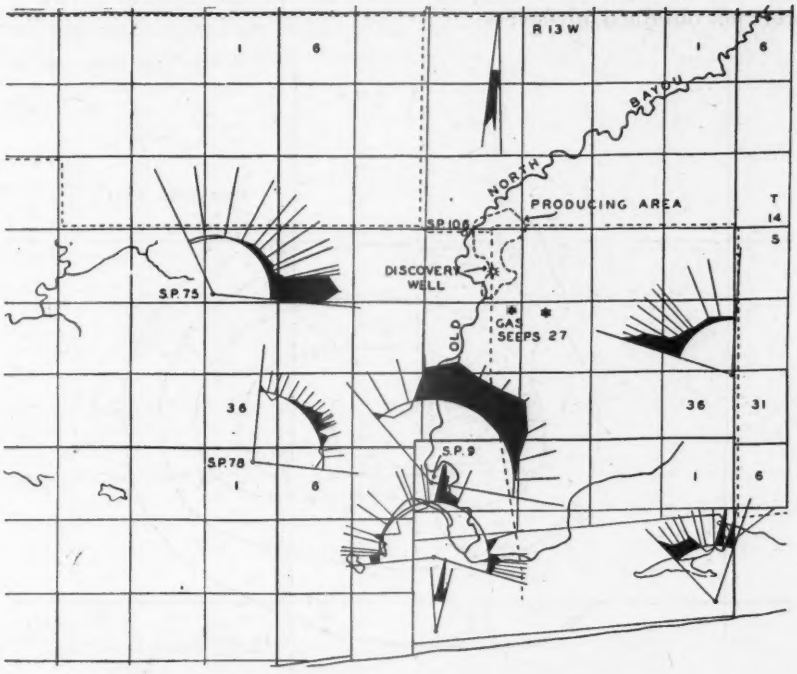


FIG. 4. Geophysical Research Corporation 1928 refraction seismograph fans with North and South profiles. Cameron Meadows, Cameron Parish, La. Refraction time leads are plotted outward from normal time arc; time lags are plotted inward. (A time lead is the amount by which the observed time at a given geophone is less than the time on the normal profile for the same distance).

was again considered strongly favorable, especially by Dr. E. E. Rosaire who was then on their staff.

b. Following the encouraging but not conclusive interpretations of the initial work, they were again engaged, in 1929, to extend their refraction work by profiles and fans, with Mr. S. H. Stuart the party chief. The combined results are shown in Fig. 4. Profiles were shot in several directions from five of the shot points to an average distance of eight miles. From these time-distance graphs normal velocity rela-

tionships were determined for the general area. Inasmuch as an interpretation of the leads disclosed by fans pointed to a salt dome in Section 21, T14S, R13W, they then profiled over the refraction-localized area of uplift from north and south in an effort to determine if salt interval velocity existed within the overall travel times. Salt velocities were not obtained, however.

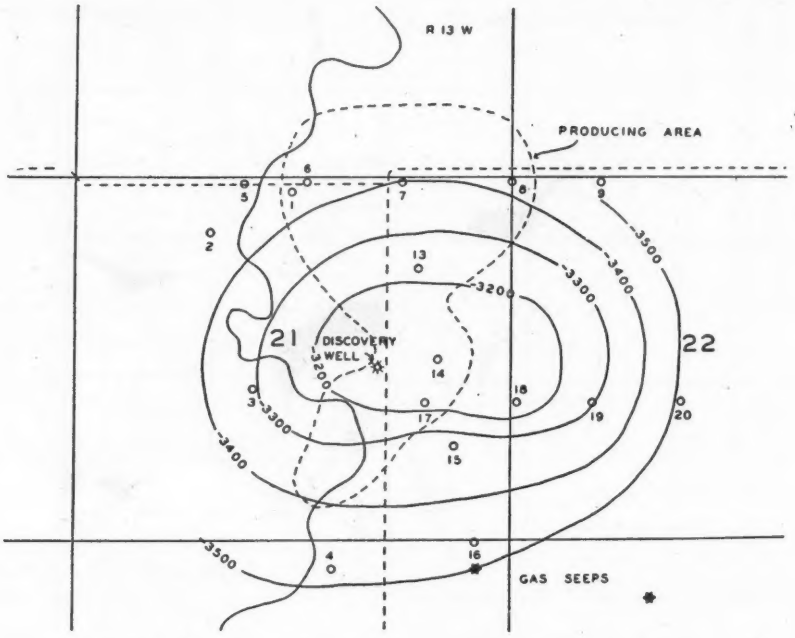


FIG. 5. Geophysical Research Corporation correlation reflection seismograph map, 1929, Cameron Meadows, Cameron Parish, La. Shot points shown by open circles. Contour interval is 100 feet.

c. Finally the refraction equipment was changed over and seventeen work days were spent in July 1929, doing correlation reflection seismograph work over the area of interest, with the results shown in Fig. 5. Comparison of their map with the salt contour map from drilled wells is proof that this was a good job in view of the limitations of early equipment and the conditions under which the work was done.

Generally, in the Geophysical Research Corporation's refraction work, fan distances were determined by blast phone, while profile distances were surveyed.

In January 1932, the merger of Vacuum Oil Company and Magnolia Petroleum Company was consummated. Hence, after that date the data from the foregoing geophysical explorations were pooled in the Magnolia Petroleum Company files.

4. With improvement in instruments and changes in shooting techniques having been made since the last survey Magnolia Petroleum Company employed Geophysical Survey, Inc., to make a dip

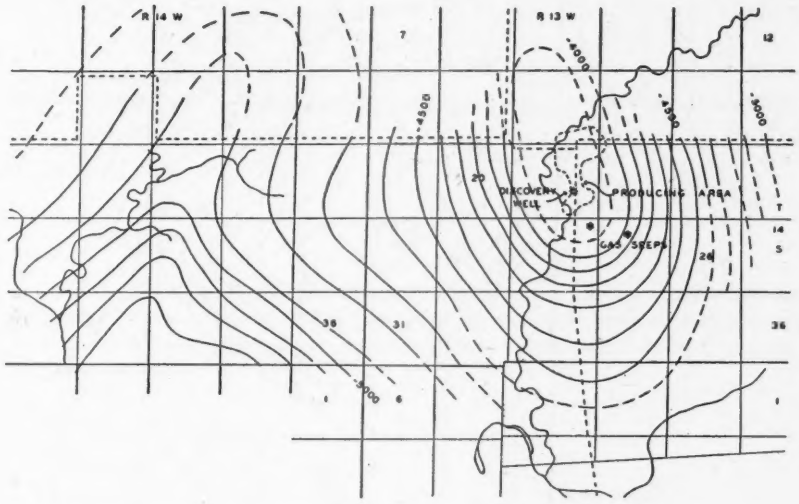


FIG. 6. Geophysical Service, Inc., 1933 dip reflection seismograph map. Cameron Meadows, Cameron Parish, La. Contour interval is 100 feet.

reflection survey of the area in June 1933. Their map is Fig. 6. At this time there were three producing wells. The survey was done to serve as a guide for further drilling.

In September 1933, Humble Oil and Refining Company acquired half interest in the Cameron Meadows lease. Subsequent development of production and geophysical exploration has, therefore, been a joint program of Magnolia Petroleum Company and Humble Oil and Refining Company.

Fig. 7 shows the shape and size of the salt mass as determined by drilling. All wells shown, both dry and producing, found salt.

5. The geophysical Research Corporation's refraction fans had indicated abnormal conditions extending from Section 21 into Section 27, T14S, R13W. Therefore, for the purpose of making a detailed

analysis of the possibility of another dome or faulting east or southeast of the SE ¼ of Section 21, where the gas seepages exist, McCollum Exploration Company was employed to make a refraction survey of the area, from January to March, 1942. They used their patented* method of lowering a detector in a well to a point at or near the salt

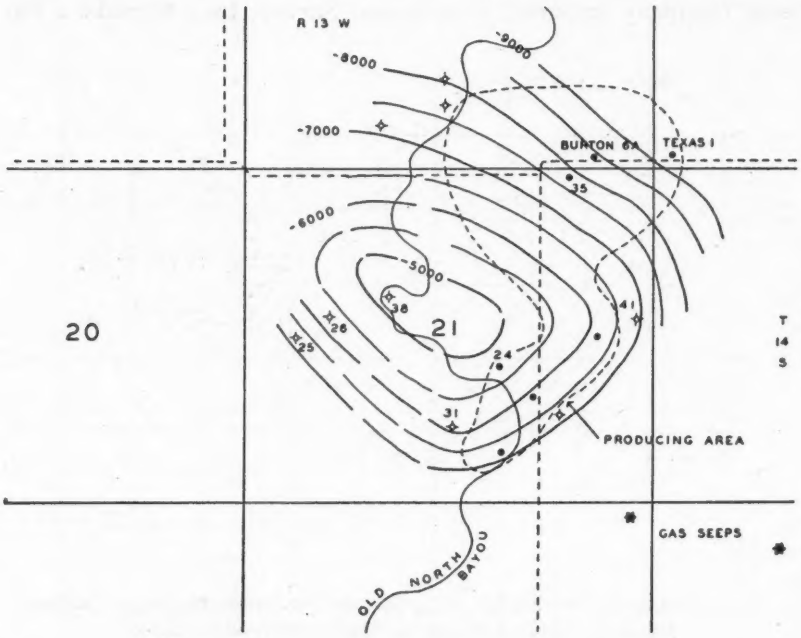


FIG. 7. Elevations of the top of the salt as indicated by drilling. All wells shown found salt. Cameron Meadows, Cameron Parish, La. Contour interval is 500 feet.

contact and recording impulses received from shot points spaced along radial lines extending across and beyond the dome. For this purpose well #35 was used, it being located on the north side of the dome near the northeast corner of Section 21. Fig. 8 shows their calculated salt contours. Note the comparison with the salt map from well control, Fig. 7.

6. Since the McCollum survey confirmed the Geophysical Research Corporation's fan leads by showing an extension of the salt mass to the southeast it seemed desirable to explore this southeastern

* U. S. Pat. No. 1,923,107.

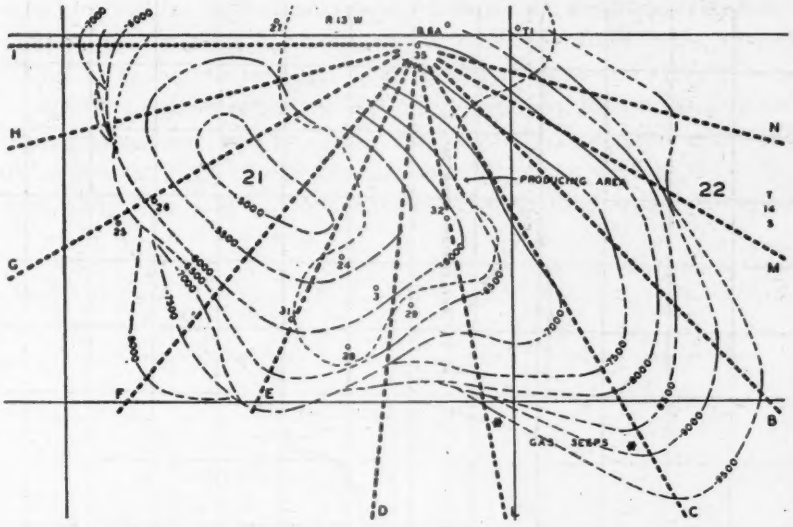


FIG. 8. McCollum Exploration Company 1942 special refraction seismograph map deducing contours on salt from recording in well #35 from shot points on lines radiating from the well. Cameron Meadows, Cameron Parish, La. Contour interval is 500 feet.

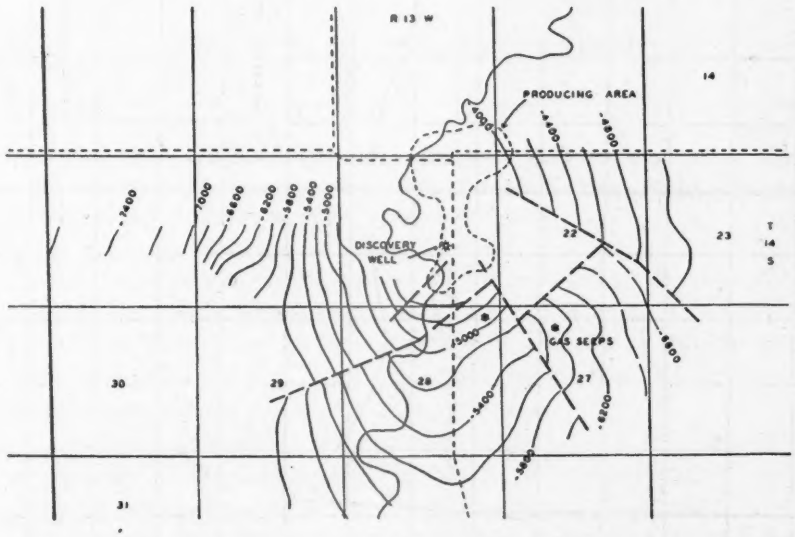


FIG. 9. Petty Geophysical Engineering Company 1942 continuous profile reflection seismograph survey. Cameron Meadows, Cameron Paris, La. Faulting is indicated by heavy broken lines. Contour interval is 200 feet.

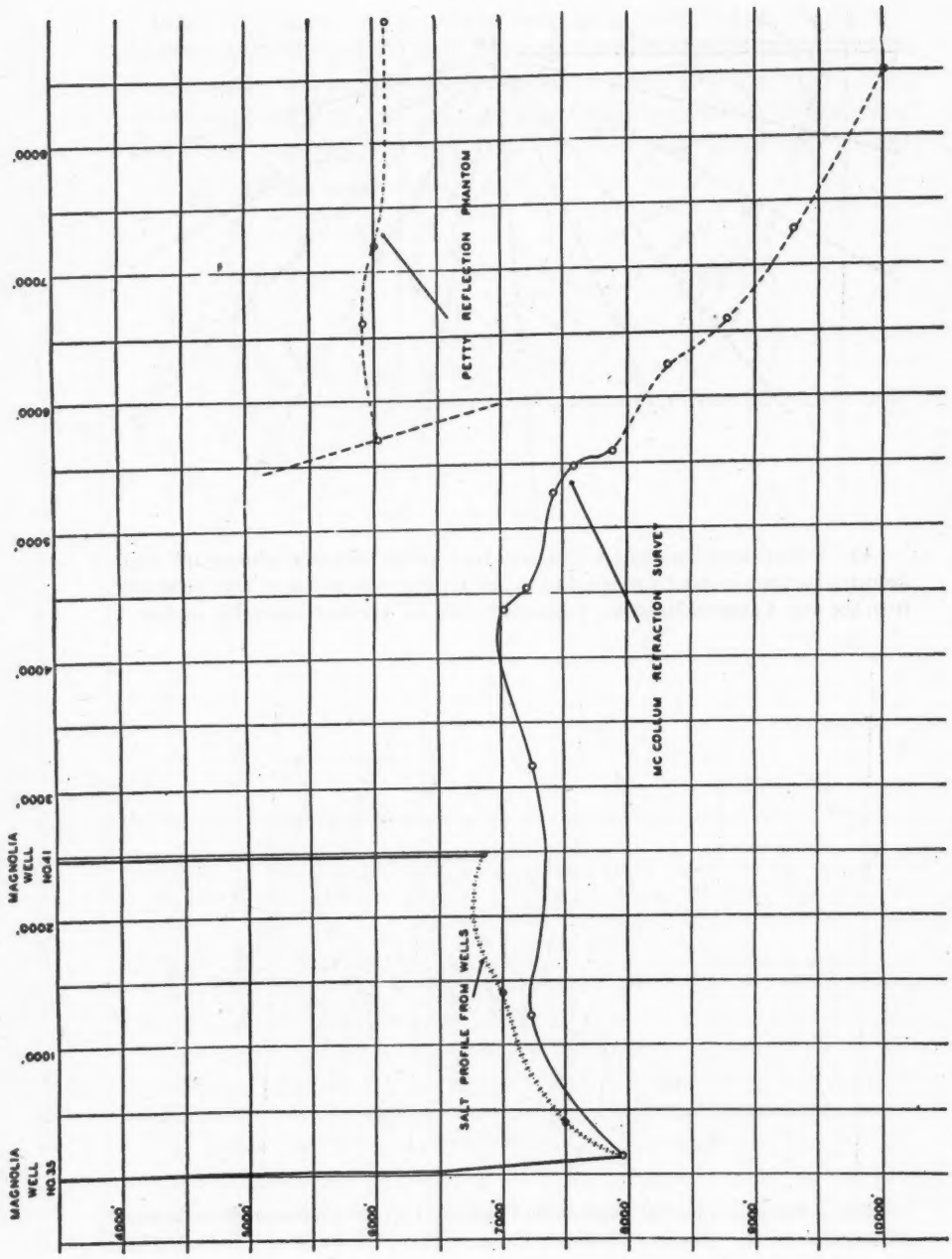


FIG. 10. Line C, McCollum refraction seismograph survey (Fig. 8) showing: 1. Salt profile from McCollum survey; 2. Salt profile from drilled wells; 3. Petty reflection phantom horizon. Cameron Meadows, Cameron Parish, La.

area in detail by the continuous profile reflection method. Petty Geophysical Engineering Company was employed, and made the survey from July to September 1942. Their findings are shown in Fig. 9.

On the profile sections by McCollum shown in Figs. 10 and 11 are superimposed the deepest Petty reflection data, together with the drilling data. Presumably the known salt depths were used by the McCollum Company for velocity adjustments that would tie their

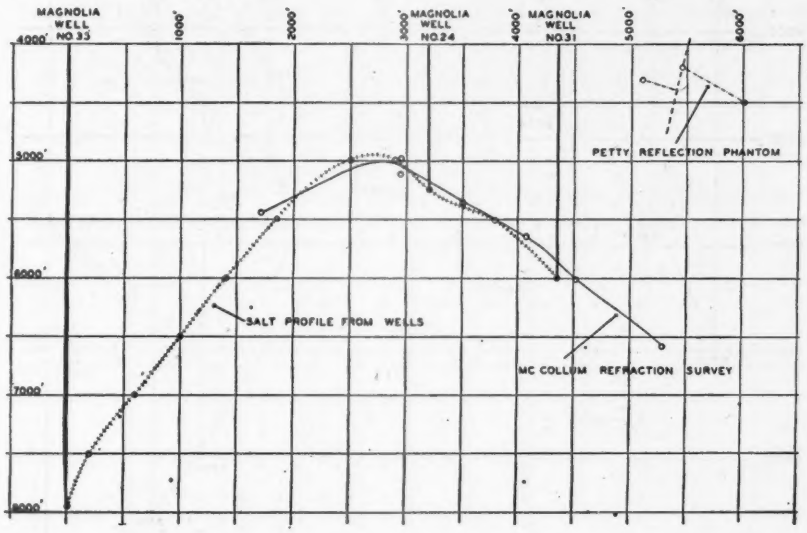


FIG. 11. Line E, McCollum refraction seismograph survey (Fig. 8) showing: 1. Salt profile from McCollum survey; 2. Salt profile from drilled wells; 3. Petty reflection phantom horizon, Cameron Meadows, Cameron Parish, La.

profiles to these known dimensions of the dome. The discrepancies may be due partly to sideswipe of the refraction rays. Well #38 on line G has been drilled to the salt since the McCollum survey was made, and it fits the McCollum prediction closely. Well #41 on line C also has been drilled to the salt since their work.

The Petty data shown is a phantom horizon, but it is at the very deepest level of the usable data. No data for this deep phantom were obtained nearer the apex of the dome than shown. Of interest is the gap of 750 to 2000 feet between the deepest reflection data and the nearest flank of the salt, and this gap spreads rapidly outward from

FIG. 10. Line C, McCollum refraction seismograph survey (Fig. 8) showing: 1. Salt profile from McCollum survey; 2. Salt profile from drilled wells; 3. Petty reflection phantom horizon. Cameron Meadows, Cameron Parish, La.

the dome. There is a vast section below 6000 feet from which no reflection data were obtained. This gap may be due to a thick section of Miocene shales with no seismic interfaces. This is indicated by the cross section made from electric logs, Fig. 12 along McCollum's line G, extended northeast to include Burton well #6A and Texas Company #1.

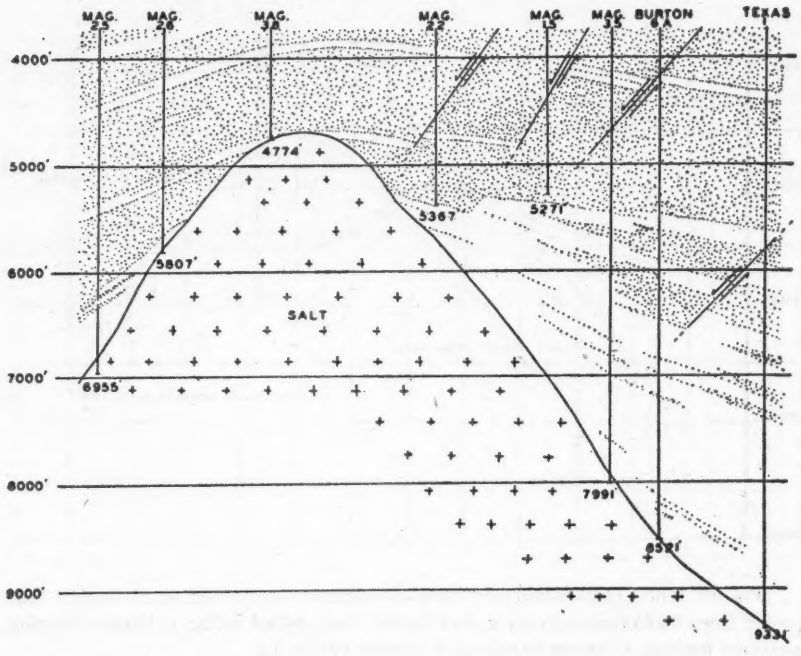


FIG. 12. SW-NE cross section of the Cameron Meadows Dome, Cameron Parish, La. (After Linn Morrow, Magnolia Geological Dept.) Sands shown dotted, shales clear.

7. In March 1943, Robert H. Ray, Inc., made a regional gravity meter survey of an area including the Cameron Meadows dome for Yegua Corporation, who have furnished us with the data pertinent to the restricted area of interest in this paper. We present it in Figs. 13 and 14, Fig. 13 being the map of the observed gravity, and Fig. 14 a map of the residual anomaly in the vicinity of the producing area.

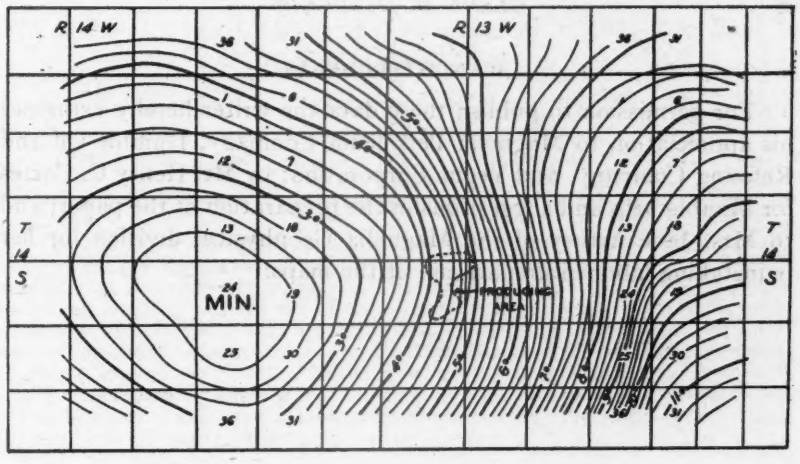


FIG. 13. Robert H. Ray, Inc., 1943 gravity meter survey for the Yegua Corporation. Total gravity contoured at 0.2 mg intervals. Cameron Meadows, Cameron Parish, La.

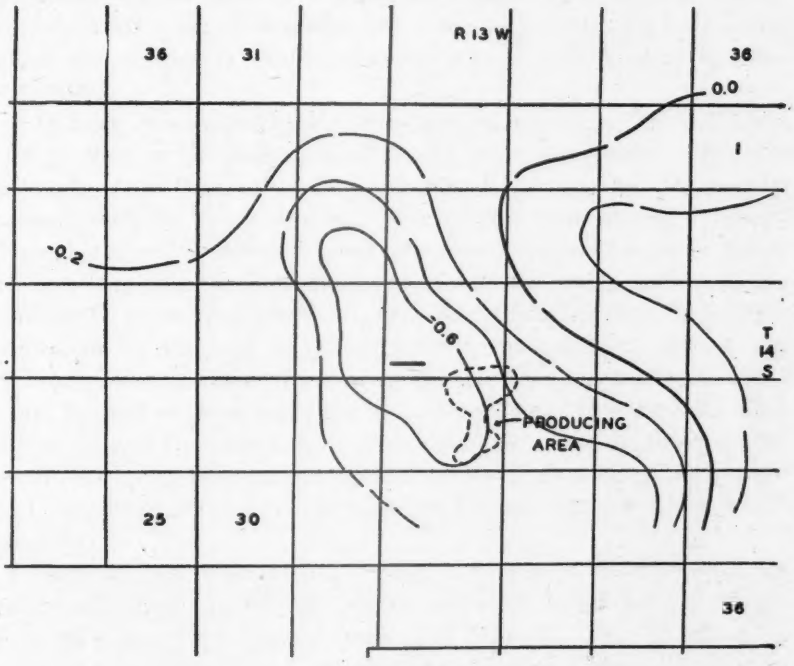


FIG. 14. Robert H. Ray, Inc., 1943 gravity meter survey for the Yegua Corporation. Residual gravity contoured at 0.2 mg intervals. Cameron Meadows, Cameron Parish, La.

ACKNOWLEDGMENTS

For permission to publish these data the writer hereby expresses his appreciation to Magnolia Petroleum Company, Humble Oil and Refining Company, and Yegua Corporation; to Mr. Henry C. Cortes for his able help and suggestions in the preparation of the paper; and to Mrs. Jane Artusy of the Magnolia Geophysical division for her painstaking labor in preparation of the maps.

EARLY REFLECTION SEISMOGRAPH EXPLORATION IN CALIFORNIA*

HENRY SALVATORI†

ABSTRACT

The first major attempt to employ the reflection method in California was made in 1931. The first results were disappointing, but by the early part of 1932 a prospect near Merced was successfully mapped. The correlation method was found to have limited applicability and the dip method was generally adopted. Most of the early work was performed with wide spacing of stations and lines since very close control was not considered necessary to discover the larger structural features which were then of greatest interest. As a result of this early reflection work several important oil fields were discovered among which are the Wilmington and Rio Bravo fields. A brief history of the discovery of these two fields is given and the seismic maps are compared with the later geologic maps compiled from well data.

INTRODUCTION

The first attempt to employ the reflection method in California was made in 1928 while the method was considered to be still in a semi-experimental stage of development. The results obtained in this first effort were not too favorable, and after a brief trial the work was discontinued.

In 1931, encouraged by the many successes achieved by the reflection method in Oklahoma, another and more determined effort was made to apply the method in California. Unfortunately, the specific areas chosen for this early work have proved to be among the least favorable in which to obtain good reflection records in the entire state. In fact, even with the latest instruments and technique, the results obtainable in these areas are very poor. The difficulties were further accentuated by the lack of proper drilling equipment to permit the drilling of shot holes to the base of the low velocity or "weathered" zone. In most of these areas the "weathered" zone is several hundred feet thick and the shot holes seldom could be drilled to the required depth. As a consequence the records obtained were exceedingly poor and the results of the work during these first months were very disappointing.

Despite these discouraging results, a reflection seismic party received sufficient support from several operators to continue its operations on a semi-experimental basis until January, 1932. At this time work was commenced on a prospect near Merced, California, and for

* Presented by title at the fourteenth annual meeting, Dallas, Texas, March 1944.

† Western Geophysical Company, Los Angeles, California.

the first time, consistently good reflection records were obtained in the state. Several fairly clear reflections occurred on most of the records and an area of several hundred square miles was mapped successfully by correlating reflections from one or more horizons. As a result of this work, a structure was discovered approximately 15 miles due south of the town of Merced. Later a test well was drilled on this structure by the Pure Oil Company and was completed in November 1934 as the discovery well of the Chowchilla Gas Field. While this gas field has proved to have little commercial importance due to the low B.T.U. content of its gas, it is of interest since its discovery resulted from some of the very earliest reflection seismograph work in California.

Early in the history of reflection work in California, it was recognized that the correlation of reflections between widely spaced points was exceedingly difficult and often impossible. In many areas of the San Joaquin Valley and the Los Angeles Basin, where most of the reflection work was performed, the character of the reflections, like the character of the rock formations, changes laterally in comparatively short distances. As a consequence, the correlation method employed in Oklahoma would not suffice, and the dip method[1] of shooting soon became standard practice. The depth and dip determinations were plotted on cross-sections, and contour maps were derived by the projection of dips along phantom horizons. Wherever possible correlations of reflections were effected as a check on the dips, but in most cases the seismic maps were based entirely on dip data.

Gradually, confidence in the effectiveness of the reflection method became more evident, but progress was slow. As late as February 1934, only four seismic parties were operating in the state. By the end of the year, however, the number of parties had increased to eleven, indicating that the reflection method had gained wide acceptance.

By the end of 1935 reflection work had been done in the San Joaquin Valley, the Los Angeles Basin, the Santa Maria Valley, the Ventura Basin, and the Sacramento Valley, with most of the work concentrated in the southern part of the San Joaquin Valley. This seismic work resulted in the discovery of several gas fields and paved the way for more important discoveries which followed.

Most of the operators interested in the San Joaquin Valley considered the oil possibilities best along the margins of the Valley, as, prior

[1] Henry Salvatori, *Correlation of Reflection Seismograph Records in California*, Bull. Amer. Assoc. Petrol. Geol., Vol. 17, March 1933, pp. 257–267.

to this time, nearly all of the oil fields were situated there. The potentialities of the valley floor were not viewed too optimistically and because of economic conditions prevailing at that time, it was thought that only structures with large amounts of closure would be commercially attractive. Therefore, in the early use of the reflection method, little consideration was given to close spacing of shot points. It was the usual practice to run lines of shot points across the valley at right angles to the regional strike with intervals between lines of three to ten miles. Shot points were spaced on the lines at intervals of three-quarters to one and one-half miles. This spacing pattern was considered adequate to locate the larger structures which were of interest, and was generally followed until later results demonstrated that smaller structures would be productive.

This early reflection campaign based on relatively loose control resulted in the discovery of several important fields. Among these the Wilmington Field and the Rio Bravo Field have been selected for historical review since the problems involved in the discovery of these two fields were fairly typical of the problems encountered in most of the early California work.

THE WILMINGTON FIELD, LOS ANGELES COUNTY, CALIFORNIA

Following the development of the Torrance Field in the Los Angeles Basin in 1925, several wells were drilled to the southeast in an effort to find a possible extension of the field in the direction of the Terminal Island region. Most of these wells were found to be structurally low and were definitely edge wells. Although one of them was completed in 1932 as a small producer in the Repetto formation (Lower Pliocene), it was not recognized that it was located on the northwest plunge of what later proved to be the Wilmington structure. The geographic relation of the Wilmington Field to other Los Angeles Basin fields may be seen from the map in Fig. 1. This map has been reproduced from the October 30, 1941 issue of the *Oil and Gas Journal*.

Early in 1936 a program of seismic work was outlined for the Terminal Island prospect and work began in February. A preliminary survey of four stations was made with shot points located as shown in Fig. 2. The points were spaced about 6000 to 8000 feet apart. At each point two profiles at right angles to each other were recorded with a total seismometer spread varying from 400 to 450 feet and with the first seismometer located approximately 25 feet from each shot point. Each profile was recorded in two directions from shot holes at either

end of the spread thus requiring three shot holes at each station. It was necessary to employ rather short spreads because of the restrictions imposed by the many industrial buildings, yards, shipping channels, etc., and also to avoid the possibility of encountering too rapid a change in the weathering zone over the length of the seismometer spread. With such short spreads it was necessary to determine the weathering corrections accurately in order to obtain reliable dip information. For this reason the two-hole method of recording was em-

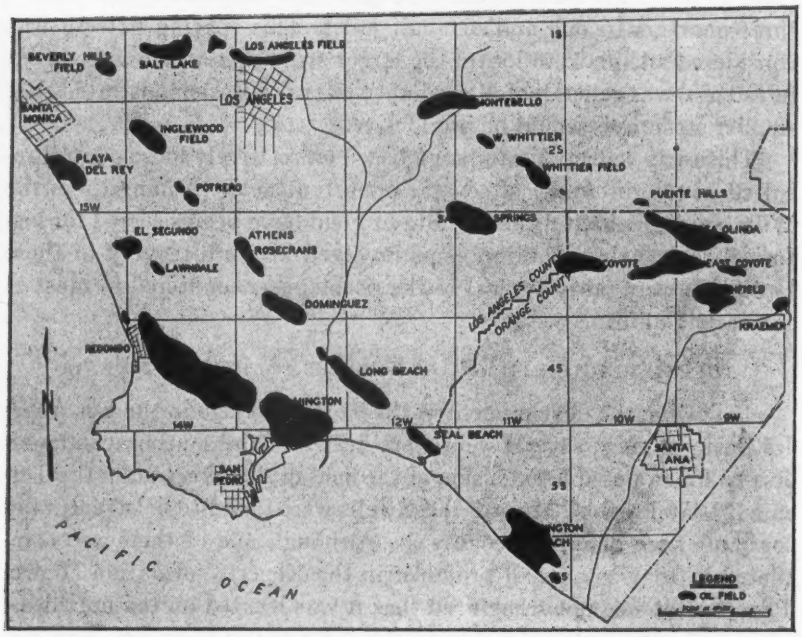


FIG. 1. Map showing Los Angeles Basin Oil Fields. Reproduced with permission from Oct. 30, 1941 issue of *Oil & Gas Journal*.

ployed in order to permit the use of up-hole times for the weathering correction at the seismometers at each end of the spread.

The reflections obtained were fair in quality and permitted the determination of reliable strike and dip data. The map in Fig. 2 shows the results of this preliminary survey. The arrows indicate the direction of maximum dip for the various zones of reflecting horizons and the magnitude of dip as well as the depth limits of the corresponding zone of reflections are given by the figures alongside each arrow in hun-

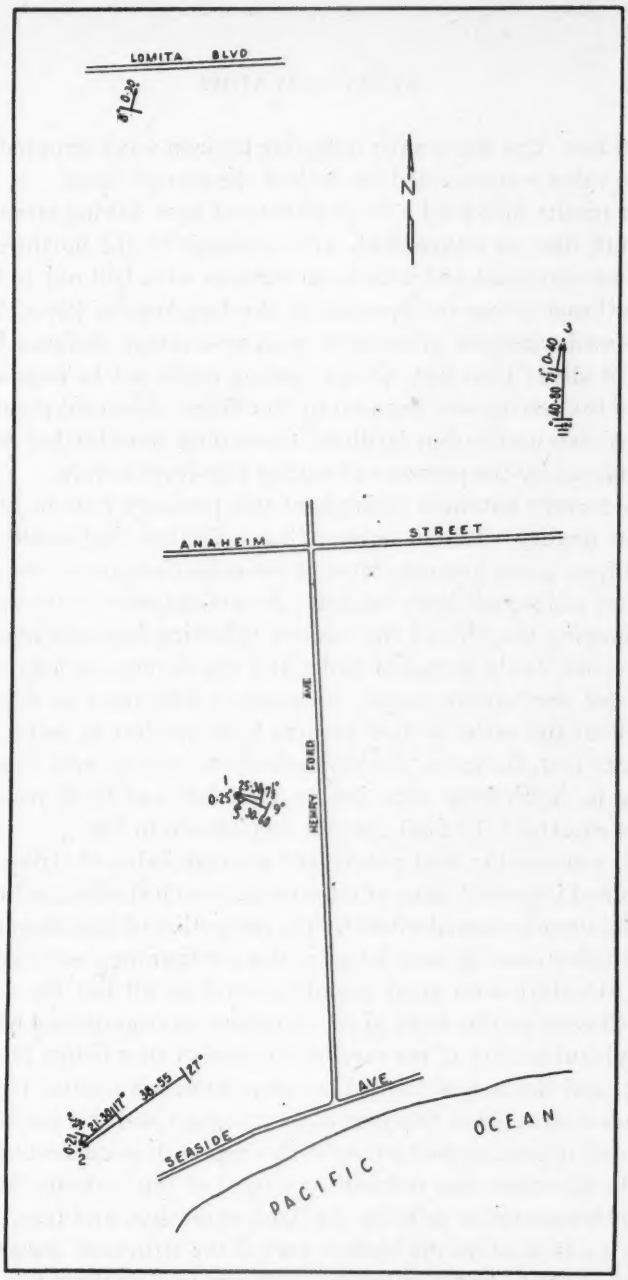


FIG. 2. Copy of original sketch map showing results of first seismic work on Terminal Island prospect. Depth limits for each zone of reflections are given by figures alongside each arrow in hundreds of feet. Shot Pt. #1 indicates N.W. dip, #2 shows S.W. dip, #3 & #4 show N. dip, thus establishing structural nose with N.W. plunge. (Survey by Western Geophysical Company for General Petroleum Corporation, February 1936.)

dreds of feet. The dip of each reflecting horizon was computed and an average value was obtained for each of the several zones.

The results indicated a large structural nose having strong north and south dips on either flank with a plunge to the northwest. The work was continued and additional stations were laid out to the east and southeast across the prospect to the Los Angeles River. Stations were placed wherever practicable with an average distance between points of about 3200 feet. Closer spacing could not be employed because of the restrictions imposed by buildings, industrial plants, shipping channels and harbor facilities. Operations were further restricted in open areas by the presence of muddy tide-level terrain.

The records obtained throughout this prospect were in general of medium quality with no outstanding reflection that could be correlated from point to point. Most of the reflections are rather sharp in character and permit fairly accurate determination of move-out times. By averaging the dips of the various reflecting horizons over rather broad zones, fairly accurate strike and dip determinations were obtained for the various zones. In general, reflections were obtained throughout the entire section varying from 900 feet in depth to more than 6000 feet. However, the best reflections were secured from a zone ranging in depth from 2000 feet to 3000 feet and these results were used to construct the final contour map shown in Fig. 3.

Fig. 3 shows the shot points, the average value of strike and dip determined from each zone of reflections at each station, and contours on a phantom horizon derived by the projection of dips from the zone of best reflections. As may be seen, this contour map outlined a large domal structure with good seismic control on all but the southeast flank. Closure on this flank of the structure was questioned because of the doubtful quality of the results obtained at shot points No. 15 and No. 17, and the lack of control between these two points. The harbor entrance is situated in this part of the prospect and this precluded the possibility of placing shot points in this region. It is interesting to note that the structure was defined by a total of ten stations. Six others were instrumental in defining the flank extension, and four, Nos. 10, 11, 13, 14, located on the highest part of the structure, were not used because of the poor quality of the data obtained at these points.

Shortly after the completion of this work, a test well was located on the northwest end of the structure near the Ford Plant. On December 6, 1936, it was completed by General Petroleum Corporation as the discovery well of the Wilmington Field. The well, known as "Terminal

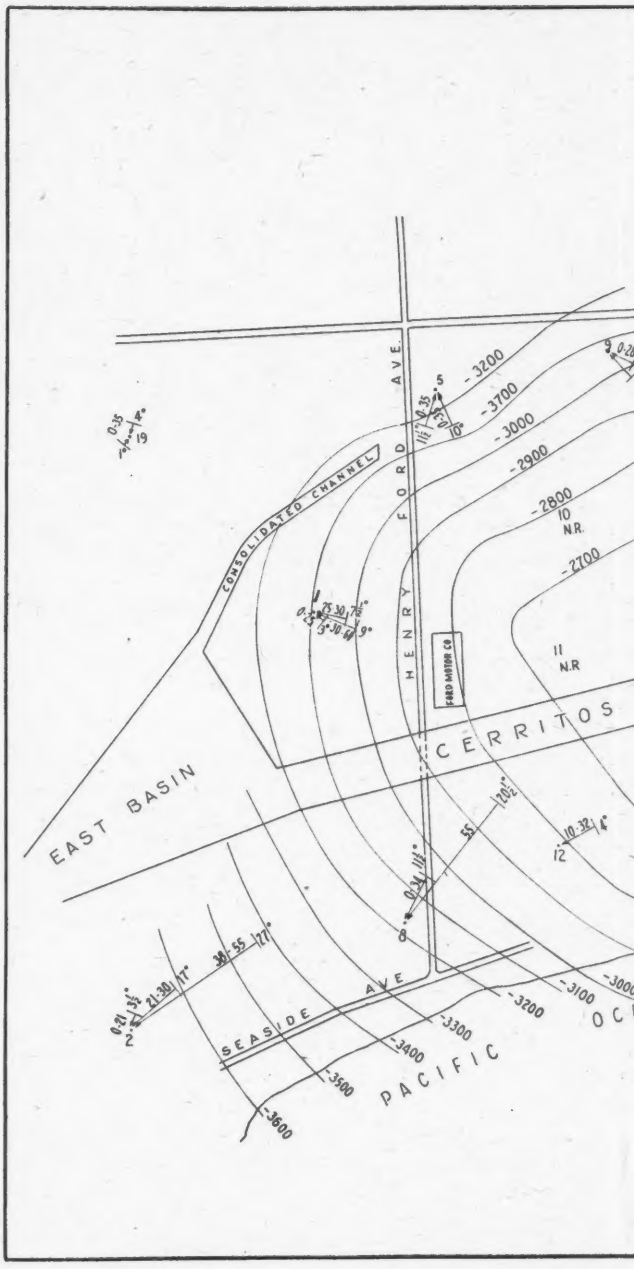
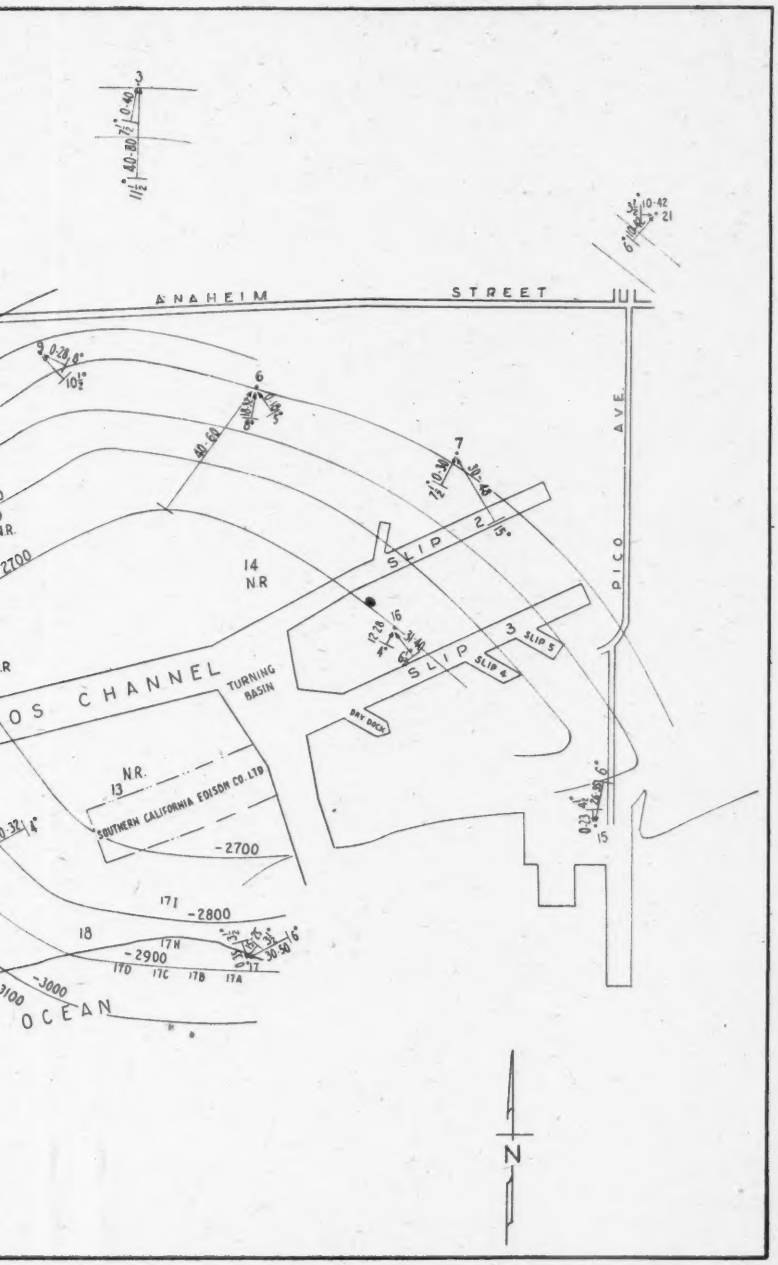


FIG. 3. Copy of original seismic map submitted on completion
reflections at approximate depth of the Ranger zone. Depth limits f
of feet. Contour interval 100 feet. (Survey by Western Geophysical



letion of field work in the Terminal Island Prospect. Contours are on zone of best imits for each zone of reflections given by figures alongside each arrow in hundreds hysical Company for General Petroleum Corporation.)

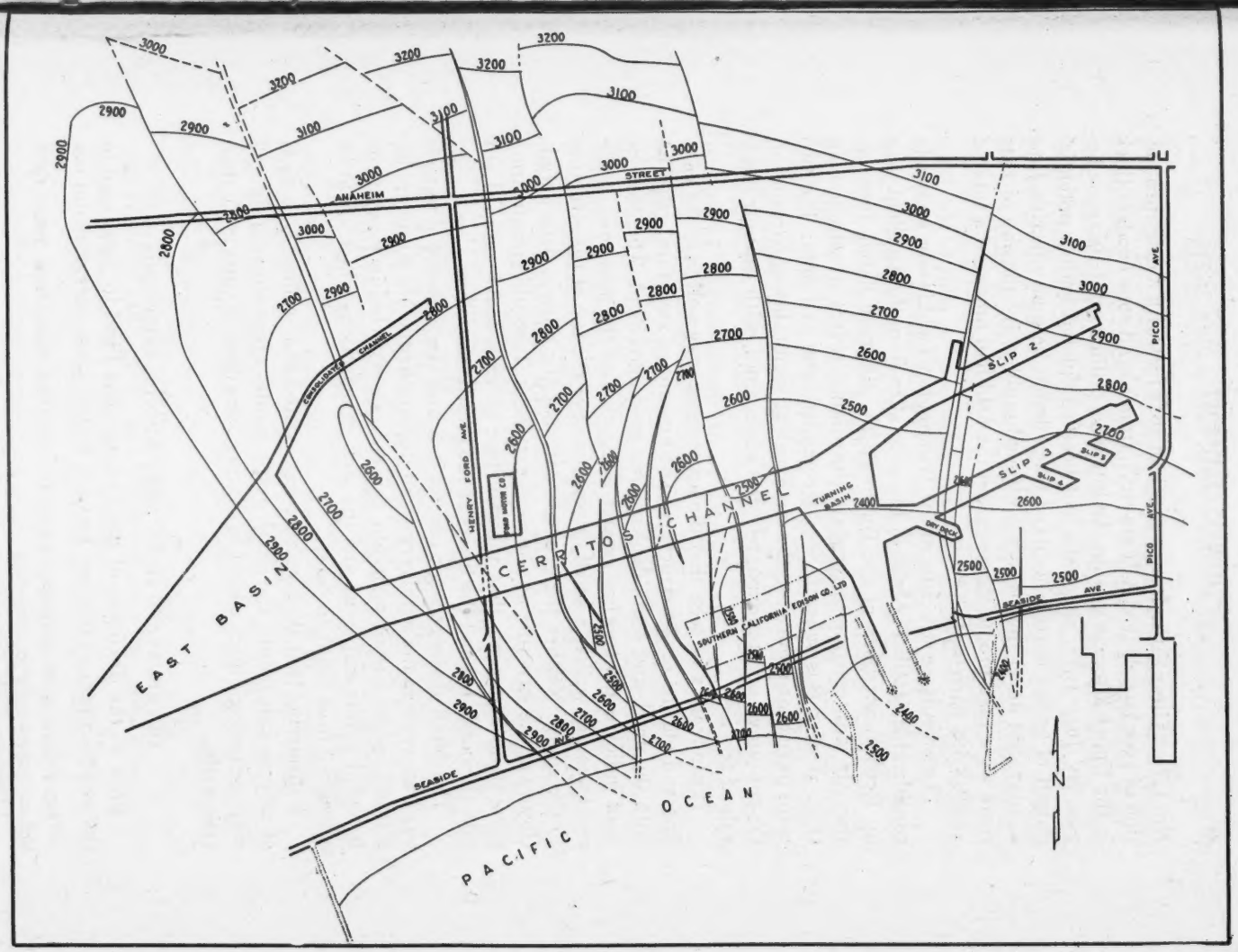


FIG. 4. Geologic subsurface map of the Wilmington Field as of June 30, 1942. Contours on "F" marker, Ranger Zone shut-off point. Contour interval 100 feet. Note absence of closure in the southeast part of the field. From a map by Reed Winterburn. (Courtesy of Union Pacific R. R.)

No. 1," was brought in from a depth of 3625 feet with a daily production of 1500 barrels (20° API gravity), from a sand zone 600 feet thick in the Upper Miocene section. An intensive drilling campaign soon began. By June 1937, 108 wells had been completed with a potential output of 65,895 barrels per day.[2] Curtailment became effective June 2, 1937, but development was continued rapidly. By the end of 1943 there were 1210 producing wells and the field had produced a total of 207,828,688 barrels of oil.[3]

The subsurface structure of the Wilmington Field is now known in considerable detail. The map in Fig. 4 is taken from the excellent map by Reed Winterburn of the Union Pacific Railroad dated June 30, 1942. It is interesting to compare the original reflection seismic map (Fig. 3) with this subsurface map compiled from well data. The two maps have been reduced to the same scale to facilitate comparison and are contoured on approximately the same zones, with contour intervals of 100 feet.

It can readily be seen that the maps agree very well as to the location and outline of the structure. The amount of structural relief on both the north and south flanks shows good agreement. The geologic data indicate a somewhat greater elongation of the axis toward the northwest, as well as a small displacement of the top of the structure to the south. Neither the geologic data nor the seismic data permit closure of the structure on the southeast flank. It would appear, from present development, that the structure extends southeastward out into the ocean beyond the limits of the present shoreline.

The detail of the geologic control indicates the presence of numerous transverse faults with very small displacements. No faults are indicated on the seismic map, but this is to be expected in view of the few shot points employed and the lack of reflections which could be correlated from point to point.

Considering that the structure was located and outlined by a total of only 20 shot points, the seismograph results agree remarkably well with the geologic map, which, in contrast, was derived from more than 1100 wells.

THE RIO BRAVO FIELD, KERN COUNTY, CALIFORNIA

Prior to the discovery of the Ten Sections Field in June 1936 in the southern part of the San Joaquin Valley, most operators did not

[2] E. J. Bartosh, *Wilmington Oil Field, California*, Bull. Amer. Assoc. Petrol. Geol. Vol. 22, August 1938, pp. 1048–1079.

[3] *Petroleum World Annual Review*, Twelfth Edition, Page 317.

consider it commercially attractive to explore possible oil producing zones deeper than 6000 or 7000 feet. Therefore, in all previous seismic work no effort was made to secure reflections from the deeper horizons. With the discovery at Ten Sections of a new zone of production in the Upper Miocene at a depth of approximately 8000 feet, seismic activity immediately increased, with interest focused primarily on the deeper horizons. During this period seismic stations were spaced at intervals of 2000 to 3000 feet along lines which were usually several miles apart. The zone of reflections of greatest interest was, of course, that corresponding to the producing zone in Ten Sections Field, namely, the Stevens sand, and all seismic maps were contoured on approximately this horizon. While deeper reflections were obtained, it was not realized until later that reflections from horizons at a depth of 11,000 feet and more were of great importance. The Vedder sand as yet had not been seriously considered as a possible producing horizon because of its great depth. In fact, even its existence in the center of the valley floor was not certain.

One of the seismic lines laid out during this exploratory campaign ran southwest across the area in which the Rio Bravo field is now situated. (The areal relation of this field to other Southern San Joaquin Valley fields is shown in Fig. 5.) This seismic line disclosed normal regional dip to the southwest, except for two points in Section 35. These two stations are designated as Nos. 2-410 and 2-411 in Fig. 6. No. 2-411 indicated a flat dip, and No. 2-410 revealed a small reversal of about $1\frac{1}{2}°$. However, as the next two points revealed no further extension of this reversal and the amount of structural relief indicated was less than that considered interesting at the time, these departures from the regional dip were not regarded as important.

The discovery of the Greeley Field in December 1936 approximately six miles north of Ten Sections Field, led to a reconsideration of small reversals. As the reversal obtained on the line traversing the Rio Bravo area occurred on what appeared to be the northwest extension of the Greeley trend, additional points were recorded on this line with shot-points spaced at intervals intermediate between those of the earlier program. The results from these additional points confirmed that reversal was present, and additional lines and points were then employed to outline a promising anticlinal structure.

Shot-points in the preliminary survey were spaced 2000 to 3000 feet apart while in the later work this spacing was halved. The seismometer spreads were symmetrical "T" spreads 800 feet long, with the shot point offset from the center point of the spread at distances

FIG. 5. Map showing Southern San Joaquin Valley oil fields. Reproduced with permission from Oct. 30, 1941 issue of the *Oil & Gas Journal*.

varying from 200 to 300 feet. At most of the stations only one profile was recorded and oriented in the direction of its associated line of shot points. At some of the more critical points on and near the top of the structure two profiles were recorded at right angles to each other in order to obtain determinations of both strike and dip. Shot holes were drilled to depths of 80 to 100 feet and charges varying from 1 pound to 20 pounds were employed.

The records obtained throughout the prospect may be classified as fair in quality, but seldom contain characteristic reflections which can be correlated from point to point. More than a dozen reflections from markers extending to a depth of more than 12,000 feet could be readily identified on most of the records. While most of the reflections are not especially outstanding, they are sufficiently sharp and distinct to permit the determination of accurate "move-out" times. The deeper reflections occurring between the times of 2.5 and 3.0 seconds are less sharp and well defined, and at a number of stations either cannot be identified or are of such poor quality as to preclude the determination of reliable "move-out" times. However, as these are reflections from horizons varying from ten to twelve thousand feet in depth, they were thought to be of minor interest at the time the field work was performed and no special effort was made to improve their quality.

Depth and dip determinations were computed from the reflection data and these were plotted on cross-sections in the usual manner. By the projection of dips a phantom horizon was drawn at the approximate depth of the Stevens sand zone which was the productive horizon in the Greeley and Ten Sections Fields a few miles to the south. This phantom horizon was contoured on a map which is shown in Fig. 6. On this map are also shown the locations of all the shot points as well as the strike and magnitude of dip computed at those stations where two profiles were recorded at right angles to each other.

As may be seen, this contour map revealed an elongated anticline having a northwest trend with a closure of about 75 feet. On the basis of this map a test well was spudded in by the Union Oil Company as its "Kernco No. 1-34" in the SE¼ of Section 34, Township 28 South, Range 25 East. The objective was the Stevens sand which was expected to occur at a depth of about 8400–8600 feet. The zone between 8463 and 8690 feet was cored and found to be composed of hard brown shale with the exception of about 1½ feet of unproductive silty oil sand, which was considered to be the remnant of the Stevens sand

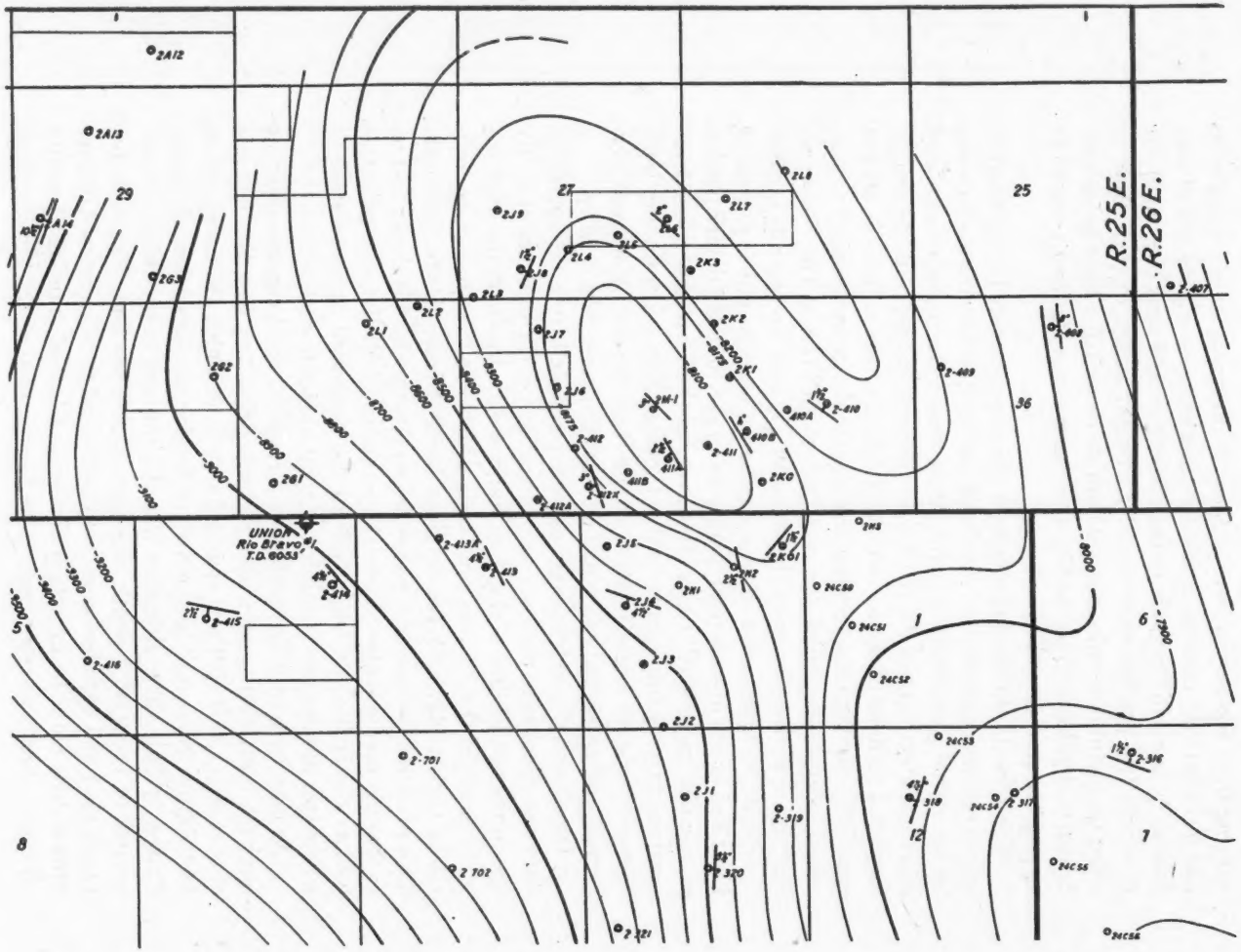


FIG. 6. Copy of original seismic map of Rio Bravo Prospect based on reflection dip data and contoured on a phantom horizon approximating the top of the Stevens sand zone. (Survey by Western Geophysical Co. for Union Oil Co., February 1937.)

and which apparently pinched out to the northwest from the Greeley Field.

While little was known of the deeper formations, the operators decided to drill deeper with the hope of discovering some new productive horizon. At a depth of 11,220 feet the Vedder sand was encountered from which the well was completed in November 1937. This well opened the Rio Bravo Field and was the first in California to produce commercially from sands below 11,000 feet. For a while it was the deepest commercially productive well in the world. The producing sand was thought to be equivalent to the Vedder sand of Lower Miocene age, which is found in fields on the east side of the valley. Two zones were found in this sand section. The upper zone was named the Rio Bravo sand and the lower was regarded as the Vedder sand.

On December 31, 1938 there were 24 producing wells in this field. By the end of 1943 this number had increased to 100, and the field had produced a total of 21,761,379 barrels of oil.[4]

In evaluating the accuracy of the seismic results it would be best to compare the original seismic map (Fig. 6) with a geologic map on an equivalent horizon. Unfortunately, no such map is available because of the absence of the Stevens sand over the greater portion of this prospect and the lack of any other recognizable geologic marker. However, during the course of field development, electric logs taken on each well reveal a correlation point at a horizon slightly above the equivalent position of the Stevens sand. Geologists refer to this as the "Q" point, and a map contoured on this horizon is given in Fig. 7.

A comparison with the original seismic map (Fig. 6) shows general agreement in structural outline, but the amount of structural relief differs. The seismic map shows a closure of about 75 feet and the electric log map has a closure of about 37 feet. Other points of difference may be noted from an inspection of the two maps, but it is clear that the seismograph results are still reasonably accurate.

After it was realized that the Stevens sand was not present in the area underlying the test well, the seismic records were rechecked for deeper reflections. Since insufficient consideration had been given to the very deep reflections at the time the survey was completed, all the records were reviewed and some additional usable reflections were identified and their corresponding "move-out" times determined. These provided additional depth and dip determinations which, to-

[4] *World Petroleum Annual Review*, Twelfth Edition, pp. 309 and 319.

FIG. 6. Copy of original seismic map of Rio Bravo Prospect based on reflection dip data and contoured on a phantom horizon approximating the top of the Stevens sand zone. (Survey by Western Geophysical Co. for Union Oil Co., February 1937.)

gether with those previously computed, were plotted on cross-sections. In addition, reflection records were secured by trade with another operator who had also run some seismic lines across this prospect, and these provided still additional control. By projecting the dips computed from the lower zone of reflections occurring between the times of 2.4 and 3.0 seconds, a phantom horizon was drawn at the equivalent

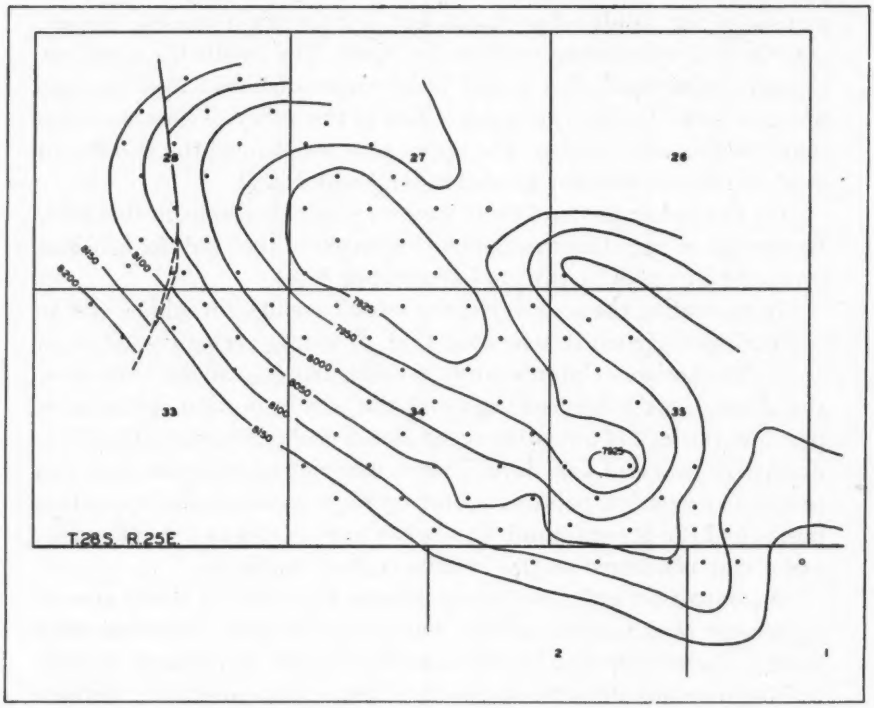


FIG. 7. Map of Rio Bravo Field with contours on electric log "Q" point in oil shale slightly higher than the horizon of the Stevens sand zone. Compare with the original reflection map on approximately the same zone in Fig. 6. (Courtesy Union Oil Co.)

depth of the Rio Bravo sand. This phantom horizon was contoured on the map shown in Fig. 8. This map was completed shortly after the completion of the discovery well and, as may be seen, indicated a structural picture similar to that shown by the original seismic map on a shallower horizon.

Development of the field was reasonably complete by May 1941, and at this time a contour map on the top of the Rio Bravo sand based

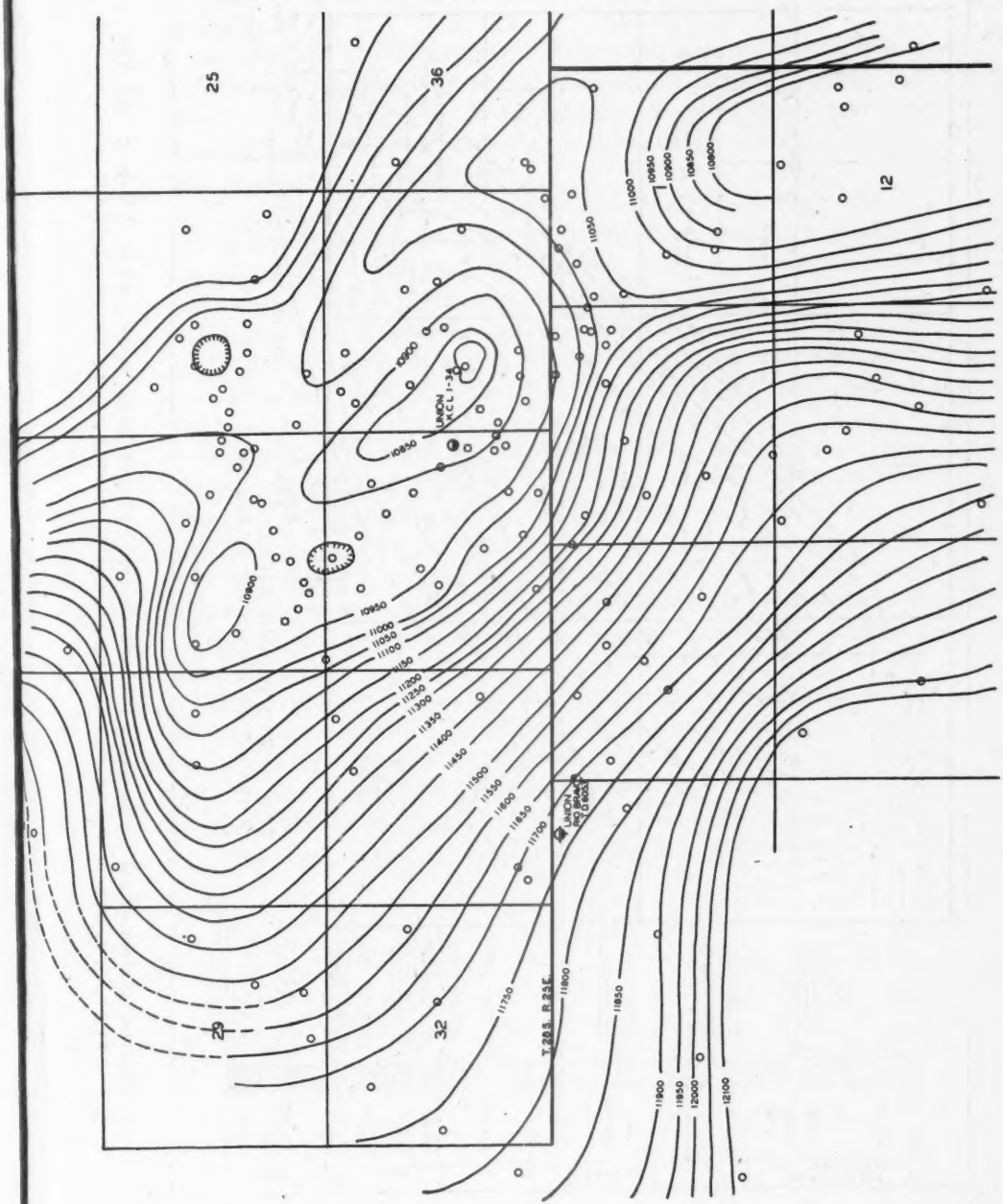


FIG. 8. Seismic map of Rio Bravo prospect based on reflection dip data and contoured on a phantom horizon approximating the top of the Rio Bravo Sand. Contour interval 50 feet. Shot points shown by open circles. (Survey by Western Geophysical Company for Union Oil Company.)

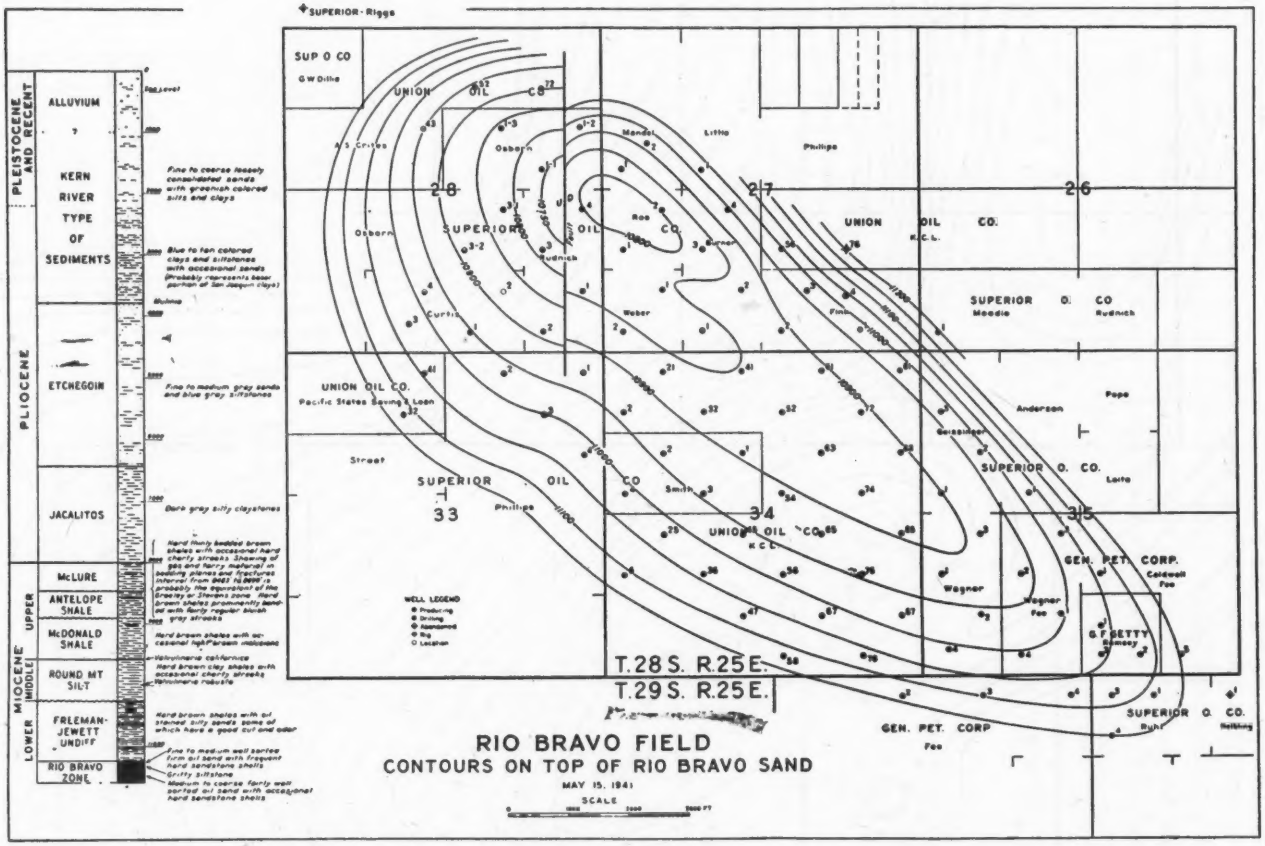


FIG. 9. Subsurface geologic map of the Rio Bravo Field with contours on top of the Rio Bravo Sand, as of May 15, 1941. The stratigraphic column for the area is given at the left. Contour interval 50 feet. (Courtesy Union Oil Co.)

on well data was prepared by the Union Oil Company. This map is reproduced in Fig. 9.

Comparison of this map with the seismic map on the equivalent horizon (Fig. 8) shows a general agreement in position, outline, and trend of the structure. The major difference is one of structural relief. The seismic map indicates a closure of about 75 feet while the geologic map shows a closure of 300 feet.

This large error in the seismic map on the Rio Bravo horizon cannot be considered surprising in view of the circumstances surrounding the compilation of this map. It is recalled that the primary objective of the survey was the mapping of horizons not exceeding 8000 to 9000 feet in depth. There was no expectation that drilling would be undertaken to a depth of 11,000 feet. The seismic map on the deeper horizon was derived from a review of the work already completed in the field and based on reflections from horizons between 10,000 and 13,000 feet in depth. No point-to-point correlations were possible, and in view of the poor quality of the deeper reflections a relatively large degree of error was to be expected. At a number of shot points reflections were not obtained from horizons as deep as 11,000 feet, and as a result the dips determined from reflections as shallow as 9,000 feet had to be utilized in drawing the phantom horizon. When all these factors are considered, it is seen that the large degree of error in the seismic results is not surprising.

In recapitulation, the Rio Bravo structure was discovered and mapped by a reflection seismic survey employing the methods of relatively loose control which were prevalent in the early reflection work in California. The results were based entirely on dip data as no correlations could be effected. In view of the problems encountered the accuracy attained may be considered reasonably satisfactory.

stratigraphic column for the area is given at the left. Contour interval 50 feet. (Courtesy Union Oil Co.)

GRAVIMETER PROSPECTING FOR CHROMITE IN CUBA*

SIGMUND HAMMER,† L. L. NETTLETON† AND W. K. HASTINGS†

ABSTRACT

As a contribution to the War Production Board's program of exploration for strategic minerals and under an arrangement with the Bethlehem Steel Company, Gulf Research & Development Company, in early 1942, made gravimeter surveys in the chromite bearing Camaguey District, Cuba. One large chromite deposit, under and between two adjacent gravity anomalies, which has been outlined to date by core drilling based on the results of this work, constitutes a substantial addition to the chrome ore reserves of the district.

Chrome ore bodies occur in or are associated with igneous rocks. Extensive density determinations of selected rock samples revealed that the chrome ore has a positive density contrast of about 1.5 with respect to the serpentine rock in which it occurs, but also that local occurrences of various other types of igneous rocks, as well as weathered surface material, cause appreciable density contrasts.

The technical aspects of the gravimeter field work are discussed. Many gravity anomalies were found; subsequent geological field work and a systematic program of test drilling proves the anomalies to arise from a variety of causes. Typical examples of gravity anomalies due to chromite deposits and to various igneous rock masses are presented. The paper concludes with brief comments on the economic significance of the work.

INTRODUCTION

In the fall of 1941, when the U. S. Geological Survey and other government agencies were greatly interested in certain strategic minerals,[1] arrangements were made for the Gulf Research & Development Company to make gravimeter surveys over certain holdings of the Bethlehem Steel Company in the Camaguey chromite district in Cuba. The work was undertaken because the known high density of chromite and its mode of occurrence, together with results of very limited torsion balance measurements, indicated that economically important results might be expected, although the problem would require the ultimate performance of modern gravimeters.

Normally, Cuba is not highly important as a source of chromite (it supplies some 15% of the total imports into the United States) but it became strategically essential when war threats to shipping were acute. The Camaguey area produces around 75% of the Cuban chromite. Except for one ore body located by the torsion balance, the known deposits there had all been found from surface exposures but considera-

* Published by permission of the Bethlehem Steel Company, Bethlehem, Pennsylvania and Gulf Research & Development Company, Pittsburgh, Pa.

† Gulf Research & Development Company, Pittsburgh, Pennsylvania.

[1] C. A. Heiland, *Geophysics in War*, Colorado School of Mines Quarterly, Vol. 37, No. 1, January 1942, especially pages 70–74.

tions of the size and distribution of these ore bodies indicated that an application of geophysical methods held considerable promise of locating substantial new chromite resources. Furthermore, and contrary to conditions in most chrome bearing areas in Cuba and elsewhere, the surface is quite flat, and, therefore, favorable for gravity prospecting; moderate or severe topography probably would make such work impossible because of the low relief of expected anomalies and the extreme precision required for their detection.

GEOLOGICAL BACKGROUND[2,3]

Chromite, which is economically important to the steel industry for use as a refractory and as a source of chromium for alloying, originates in ultra-basic igneous rocks. Commercial accumulations of chromite almost always occur in serpentine, formed by alteration of the ultra-basic rocks. The serpentine belt in the Camaguey district of Cuba is within the great belt of igneous rocks forming the backbone of the island. The serpentine itself contains local bodies of gabbro, anorthosite and other varieties of igneous and metamorphic rocks, as well as the chromite bodies. Much of the surface is covered with laterite (a red clay derived from weathering of the serpentine) which rests on a somewhat irregular rock surface, so that the laterite thickness varies quite locally by several feet. Some of the chromite or igneous bodies are exposed but, for the most part, laterite and alluvium blanket the area.

In Cuba, workable chromite deposits are either primary ore bodies within the serpentine or chromite "float," left on the surface by weathering of the serpentine. The primary ore bodies in the Camaguey district are extremely irregular "sackform" masses in the serpentine rock. No alignments or trends have been recognized in the distribution of the ore bodies either horizontally or in depth, and they appear to occur at random mixed in the serpentine matrix, much as plums might be mixed in a pudding.[4] The size of known individual deposits varies from small "pods" with dimensions of a foot or less to large bodies with dimensions of 200 to 400 feet and containing over 100,000 tons of shipping grade ore. The Camaguey ore may range from almost pure massive chromite $[(Fe, Mg)\,O \cdot (Cr, Al, Fe)_2O_3]$ to country rock containing only a small percentage of chromite. On account of its chemical com-

[2] T. P. Thayer, *Chrome Resources in Cuba*, U.S.G.S. Bulletin 935-A, 1942.
[3] W. Lindgren, *Mineral Deposits*, McGraw-Hill, 4th Edition, 1933.
[4] Thayer, *op. cit.*, p. 25.

position, much of the Camaguey chromite is admirably suited for refractory use. The shipping grade ore usually contains less than 10 per cent gangue by weight.

GEOPHYSICAL PRINCIPLES

The applicability of the gravity method of prospecting is fundamentally dependent upon the existence of density contrasts between the rocks of interest. Rock densities determined during the course of the gravimeter field work in Cuba are summarized in Table I. The essential fact from these data for the problem under consideration is that chrome ore has a density contrast of about +1.5 with respect to the serpentine country rock. The problem, therefore, is to recognize positive gravity anomalies resulting from chromite deposits sufficiently large and shallow to be commercially valuable.

TABLE I. ROCK DENSITIES, CAMAGUEY DISTRICT, CUBA

Material	No. of Samples	Density	
		Range	Average
Chromite	22	3.60–4.19	3.99
Chromite, disseminated	3	3.25–3.56	3.40
Serpentine	42*	1.97–2.74	2.51
Gabbro	11	2.75–3.03	2.90
Gabbro, weathered	3	2.18–2.37	2.30
Troctolite	2	2.78–2.81	2.80
Dunite	1	—	2.50
Limestone	2	2.71–2.73	2.72
Anorthosite	1	—	2.68
Soils			
Laterite	5	1.20–1.71	1.43
Disintegrated Serpentine	1	—	1.38

* One sample of density 1.63 omitted because of rare occurrence.

Estimated Abundance of Rocks

Serpentinized Peridotite	83%
Serpentinized Dunite	12%
Troctolite	3%
Gabbro	1%
Other	1%

With an anticipated instrumental probable error of about 0.02 mg, the smallest gravity anomaly which we could hope to observe reliably should have a relief of about 0.05 mg. The relation between size and depth of chrome ore bodies (assumed spherical and uniform, and with density 4.0, density contrast 1.5) which would produce a gravity anomaly of 0.05 mg is indicated in Table II.

TABLE II. SIZE AND DEPTH OF SPHERICAL CHROMITE BODIES GIVING 0.05 MG ANOMALY

Ore mass in tons	31	1,000	10,000	100,000
Depth to top of ore body in feet	0	10	43	163

Ore bodies of such size and depth are definitely of commercial value, and, therefore, it was decided that we must be prepared to look for gravity anomalies with relief as small as 0.05 mg and areal extent of some tens of feet. As a reasonable compromise between adequate coverage and useful rate of areal progress, a station spacing of 20 meters in a square array was chosen, recognizing that this spacing could miss many small and shallow, but commercially valuable ore bodies.

FIELD OPERATIONS

The surface in the Camaguey district is very favorable for gravimeter operations; the country is very flat, except for some disturbances due to mining operations, and is open, aside from local occurrences of brush. Surveying and gravimeter operations were conducted simultaneously and on foot by three men. The Gulf gravimeter[5] was carried by hand from station to station and was transported by motor truck only to and from the field and on periodic trips to a base station as discussed below. Almost all of the stations were located in a regular grid spaced 20 meters each way. Possibly interesting one-station indications were "five-spotted" by placing additional stations around them at 5 or 10 meter distance and re-observing the central stations for verification and detail.

The party personnel consisted of four men: party manager, gravimeter operator, surveyor and computer. Other help, when needed, was hired locally.

Field work was initiated on January 22, 1942, and discontinued on July 14, 1942, a total of 5,320 stations being made. The work was done in several scattered small areas, mostly on properties of the Bethlehem Steel Company. The total area covered is about 212 hectares—approximately 520 acres or 0.8 square mile. The individual surveys were not tied together gravitationally or horizontally, as many of them were too far apart for this to add materially to their practical utility.

On account of the need for the utmost precision, great care was exercised in both gravimeter and associated surveying operations. The gravimeter was read to the nearest 0.01 mg and standardization read-

[5] R. D. Wyckoff, *The Gulf Gravimeter*, GEOPHYSICS VI, pp. 13–33, January 1941.

ings to determine instrumental drift, including tidal gravity variations, were taken at a base station within the survey at intervals of about one hour. Station positions were determined by stadia and pacing to within two meters and leveled to within five cms. The attained precision of the gravimeter readings, as measured by the difference on all re-observed stations, is indicated by the following table.

TABLE III. FREQUENCY OF GRAVITY DIFFERENCES ON RE-OBSERVED STATIONS

Difference between readings in mg	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13
Frequency	95	126	137	101	64	46	27	23	9	7	3	0	0	1
Normalf requency	103	190	148	99	56	27	11	4	1	0	0	0	0	0

From these data the average difference is 0.028 mg which gives the probable error of a single observation to be 0.016 mg.* Bouguer anomaly values of the stations were calculated in the usual way using a surface density of 2.4, which was adopted arbitrarily at the beginning of operations before density data were available. The correctness of this figure is questionable but it is not critical because of the very flat terrain. Where appreciable, usually due to dumps and pits from mining operations, terrain corrections were calculated using terrain correction tables[6] in which the inner zones had been subdivided for higher accuracy. The various reduction factors were determined with sufficient precision so that the combined uncertainty resulting therefrom was no greater than the uncertainty in the gravity measurement.

The constancy of the sensitivity of the gravimeter was checked by periodically observing the gravity difference between a pair of selected calibration stations with a gravity difference of about 17 mg. These check readings all agreed within 0.02 mg, showing that the gravimeter sensitivity was stable to 1/10 per cent during the six months of field operations in Cuba.

RESULTS

A test survey was made over a known chromite deposit which had not been rendered unsuitable for the purpose by extensive stripping and mining operations. Fig. 1 shows that this ore body produces a clear and unmistakable gravity anomaly with gravity relief of 0.35 mg and areal extent in close conformity with the outline of the ore body.

* This result is based on the usual assumption that the data obey the Normal Error Law. There is some indication that these data deviate from this Law but this technical question will not be considered further here.

[6] Sigmund Hammer, *Terrain Corrections for Gravimeter Stations*, GEOPHYSICS IV, pp. 184–194, 1939.

Exploratory drilling shows the deposit to occur in a depth range from the surface down to 70 feet and indicates that the mass of ore is some 40,000 tons. It is quite evident that a chrome ore body of this size and

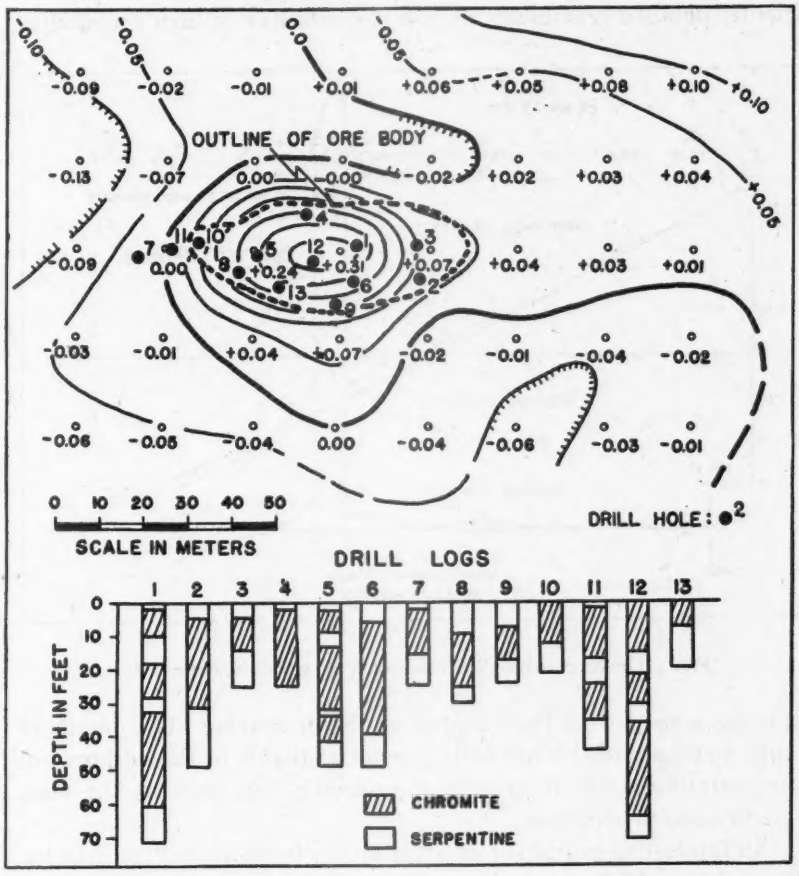


FIG. 1. Gravity anomaly over known chromite deposit, and logs of drill holes whose locations are shown by solid circles. Gravity values (Bouguer anomaly) in milligals. Contour interval 0.05 mg. Heavy dashed line shows outline of ore body.

depth would not fail to be revealed by a gravimeter survey with the spacing and precision used in this work.

Another test survey over a much smaller known ore body is shown in Fig. 2. This survey consisted of a single traverse with stations strategically placed to measure the full gravity effect of the ore body. Di-

rectly over the deposit the station spacing is 5 meters, increasing to 10 meters and finally to 20 meters at the two ends of the profile. A distinct local positive gravity feature of 0.05 mg relief is indicated, proving that a chromite deposit of this size and depth can be found with sufficiently detailed gravimeter work but would have a high probability

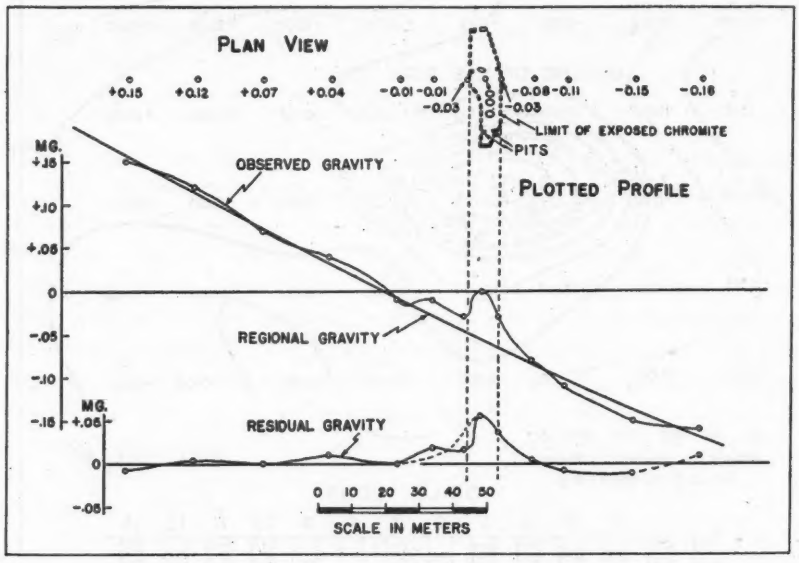


FIG. 2. Gravimeter profile across small, known chrome ore body.

of being missed with the adopted 20 meter spacing. The details of depth and mass of this ore body are not available to the authors but interpretative calculations from the gravity data indicate the mass may be 2000 to 3000 tons.

An interesting portion of an areal survey is shown in Figs. 3 and 4. The "observed" Bouguer Anomaly gravity values and contours are mapped in Fig. 3 and the "residual" gravity results, after removal of the "regional" influence (shown by smooth, dashed contours in Fig. 3) are given in Fig. 4. Two anomalies, indicated as "1" and "2" on Fig. 4, were outlined on the basis of these data, and subsequent core drill tests have proved both of them to be associated with a single, very large chromite deposit with a thin portion between the two gravity anomalies. The ore occurs as irregular lenses dipping to the north and east and is found in the depth range 130 to 275 feet under Anomaly 1

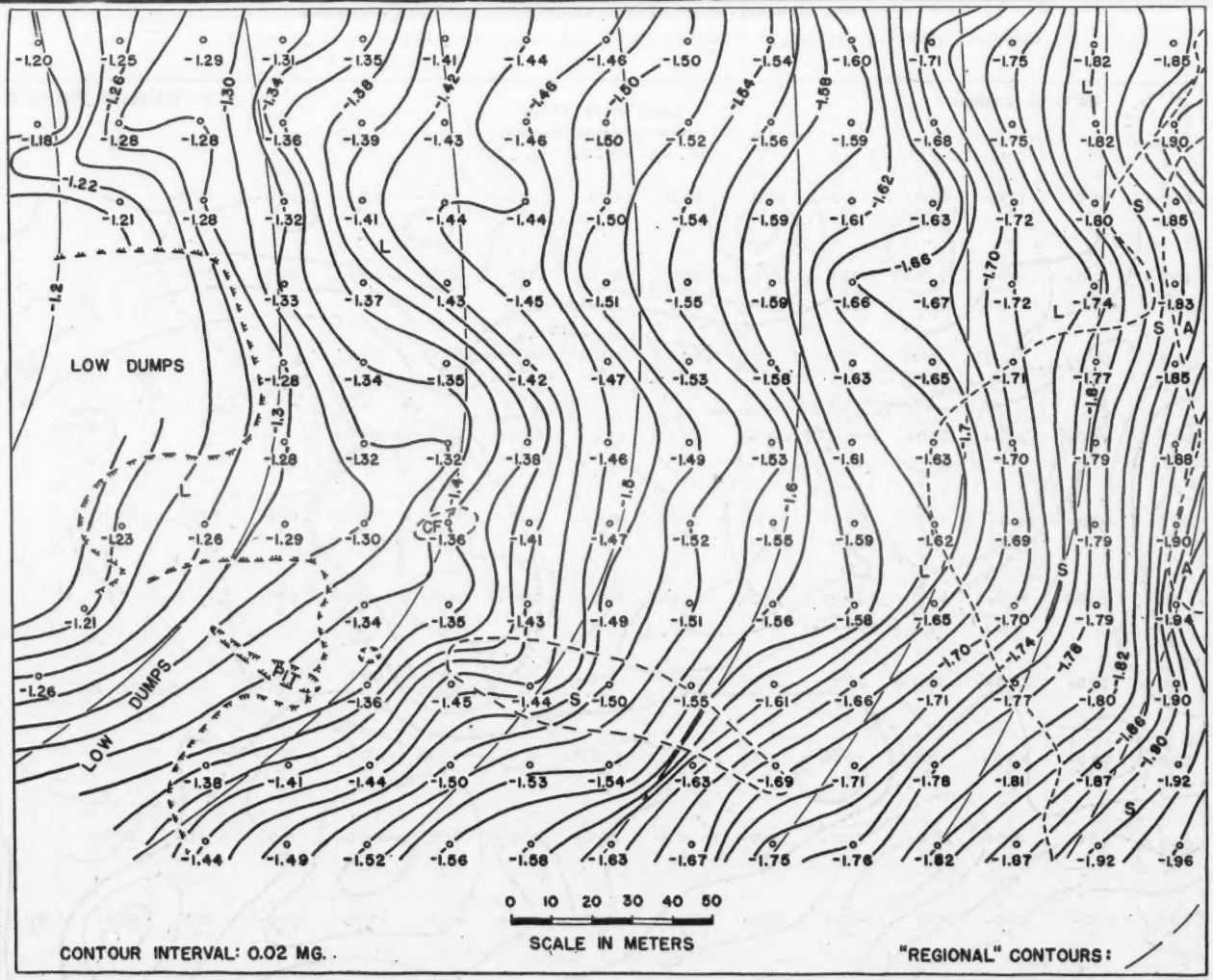


FIG. 3. Bouguer anomaly map of portion of areal survey. Surface geology: A—alluvium, L—laterite, CF—chrome float, S—serpentine. Regional contours are shown as light dashed lines trending south and southwest.

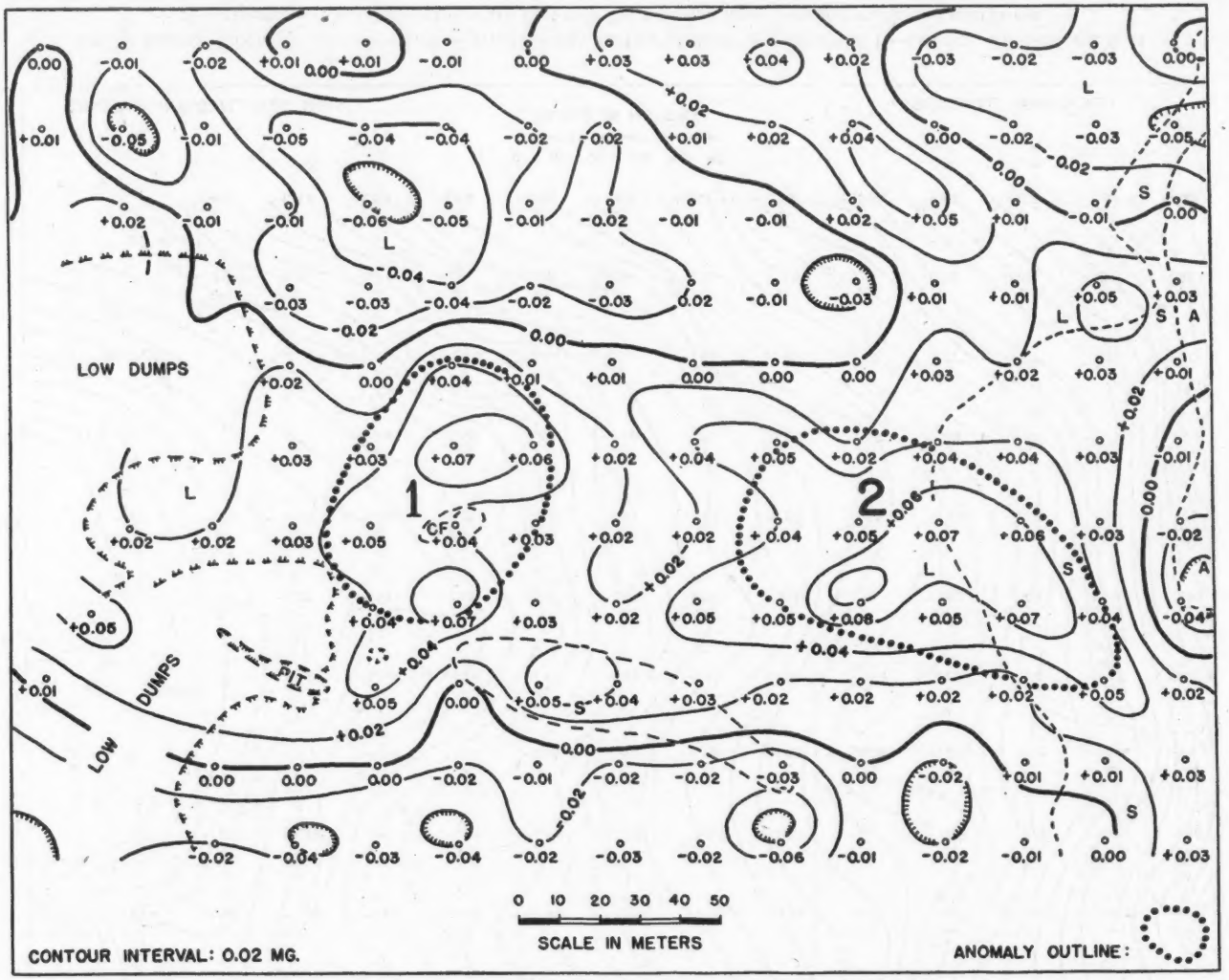


FIG. 4. "Residual" gravity map derived from Fig. 3 by subtraction of "Regional" gravity, showing

and 175 to 500 feet under Anomaly 2. In plan, the over-all length of the ore body is over 600 feet and it varies from less than 100 feet to about 200 feet in width. We understand that the ore body as delimited to date by test drilling is in substantial agreement with the outlines of

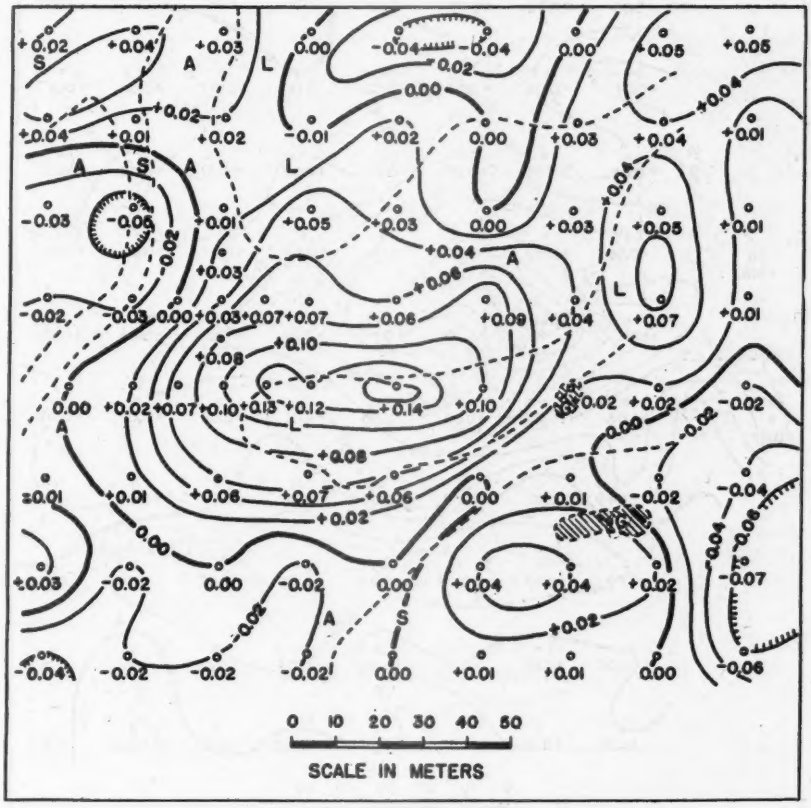


FIG. 5. Gravity anomaly due to anorthosite in serpentine. Surface Geology: A—alluvium, L—laterite, S—serpentine, G—gabbro.

the gravity anomalies, aside from the thin connection between them mentioned above.

Two especially impressive gravity anomalies are shown in Figs. 5 and 6. Test drilling proved the gravity anomaly in Fig. 5 to be closely associated with a compact body of anorthosite in the serpentine rock; drilling found the top of the anorthosite at a depth of 5 feet. Similarly,

FIG. 4. "Residual" gravity map derived from Fig. 3 by subtraction of "Regional" gravity, showing anomalies which led to discovery of large, deep chromite deposit.

the anomaly in Fig. 6 was proved by several holes to indicate a gabbro body. This was not altogether unexpected because of the small surface exposure of gabbro within this gravity feature.

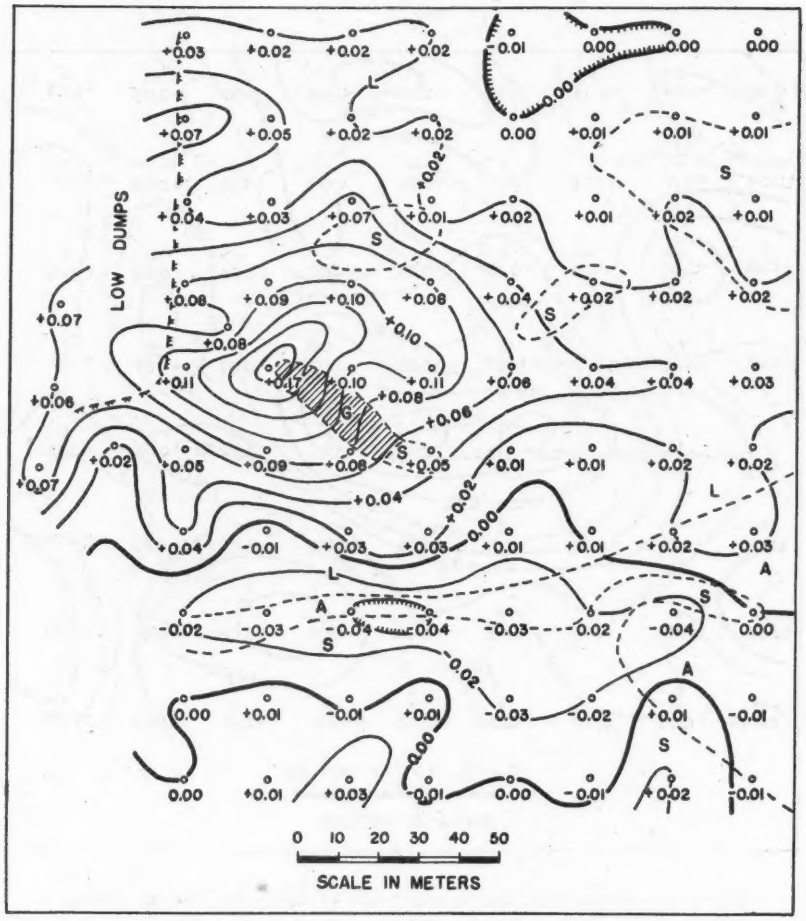


FIG. 6. Gravity anomaly due to gabbro in serpentine. Surface Geology: A—alluvium, L—laterite, S—serpentine, G—gabbro.

Two small gravity anomalies, suggestive of the type found over a small, shallow ore body (Fig. 2) are shown in Fig. 7. These indications were confirmed and detailed by "five-spots" of gravimeter stations with a ten meter spacing. Both features were disproved as chrome ore

prospects by test drilling. The cause of these anomalies is not known to the authors. The one on the left could be due to variable thickness of the lateritic soil overlying the dunite which outcrops at the anomaly. The measured density contrast of 1.0 between these two formations requires only a five foot thickness of laterite around the outcrop

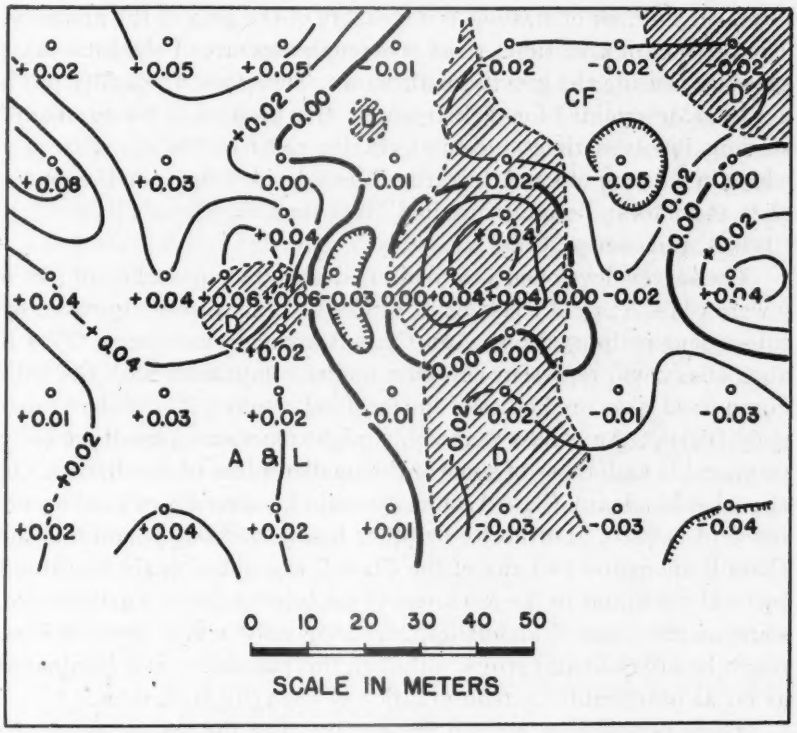


FIG. 7. Typical small gravity anomalies showing "five-spotting" of stations for confirmation and detail. Surface geology: A—alluvium, L—laterite, CF—chrome float, D—dunite.

to account for the gravity feature. This obvious and simple explanation cannot apply to the other anomaly, as the dunite outcrop is much more extensive than the gravity feature.

EVALUATION AND CLASSIFICATION OF ANOMALIES

In a survey taxing limiting performance of instruments, a large number of anomalies of some kind or other is almost certain to result.

The problem then arises of evaluating the various features and of finding some objective basis for grading the anomalies as relatively good and poor prospects.

An arbitrary grading was made on the basis of the number of stations within, and the maximum gravity relief of each anomaly, as shown on residual gravity maps. Since the station spacing was uniform, the number of stations is a measure of the area of the anomaly. The product of area times relief is a rough measure of the total mass anomaly causing the gravity disturbance. Therefore, a "quality product" was determined for each anomaly; this product is the number of stations involved times the total gravity relief of the anomaly as a whole in 0.01 mg units. Arbitrarily it was decided to grade the anomalies as follows: "quality product" less than 25, Class C; 25 to 50, Class B; and over 50, Class A.

The survey developed a total of 113 designated anomalies, of which 6 were Class A; 19 of Class B; 84 of Class C and 4 were disproved by subsequent reobservations. Any Class A anomaly and many Class B anomalies could represent chromite bodies comparable with the half-dozen or so large ore bodies of the most important mines of the Camaguey District. Any Class C anomaly might represent a small ore body comparable with those of some of the smaller mines of the district. On the other hand, any Class A anomaly could be caused by a local occurrence of gabbro, anorthosite or other heavy rocks and many of the Class B anomalies and any of the Class C anomalies might be caused by local variations in the thickness of the laterite cover. Furthermore, some of the Class C anomalies, involving only a very few stations, might be instrumental errors, although this possibility was eliminated as far as practicable by reobservation of the critical stations.

These possibilities make it imperative that the gravity survey be followed by core drilling to determine the causes of the various anomalies. This procedure has been followed and all of the anomalies of Class A, most of those of Class B and many of those of Class C have now been tested. These tests have shown that all of the Class A anomalies and some of the Class B anomalies are caused by local bodies of gabbro, anorthosite and other dense rocks. The two adjacent Class B anomalies of Fig. 4 are caused by a very large chromite body. None of the other anomalies tested has indicated significant chromite occurrences.

The depth of drilling required to test a given anomaly can be lim-

ited by the nature of the anomaly itself.[7] Obviously, a very local anomaly must arise from a shallow cause and broad anomalies may arise from deeper causes. For each anomaly, the maximum depth of the possible disturbing mass was calculated and this figure recommended to control the depth of the test drilling.

DISCUSSION

The selected gravity features presented above show that, with favorable surface conditions, prospecting for chromite deposits similar to those in the Camaguey area is quite feasible with modern high precision gravimeters, as large ore bodies within present commercially exploitable depths produce quite outstanding gravity anomalies. Relatively small but very shallow ore bodies also may be found by gravimeter prospecting but the chance of overlooking them is high with a 20 meter station spacing. However, it is clear that interesting-appearing gravity anomalies can arise from a variety of causes not related to chromite occurrences. Therefore, a systematic program of test drilling to evaluate the gravity indications must be considered to be an essential part of such a prospecting program.

The Bethlehem Steel Company has reported[8] that geological field work and extensive test drilling on the gravity anomalies have shown that the positive gravity features are due to one, and sometimes more, of the following relationships.

1. Dense serpentine in less dense serpentine.
2. Gabbro masses in serpentine.
3. An area of shallow limonitic mantle surrounded by an area of deeper limonitic mantle.
4. An outcrop of compact serpentine or gabbroic rock surrounded by similar material but weathered.
5. Chromite in serpentine.

From the number and variety of possible causes it is to be expected that a large proportion of the anomalies found should prove disappointing. On the other hand, the absence of a gravity anomaly is very strong evidence against the existence of a substantial chromite deposit in the area covered for it has been established that chromite

[7] L. L. Nettleton, *Geophysical Prospecting for Oil*, McGraw-Hill, 1st Edition, 1940. pp. 122–125. "Depth Estimation."

[8] W. L. Cumings and D. M. Fraser, *Gravimeter Survey for Chromite in Cuba*, A.I.M.M.E. Meeting, New York, February 15–18, 1943. (Not Published.)

has a higher density than any of the other rocks occurring in the area. In other words, a positive gravity anomaly is a necessary but not a sufficient indication of a chromite body. This statement applies to most ore bodies which might be of economic interest but obviously does not include deposits which are small and shallow, and happen to be so located as to miss having an appreciable effect on the gravimeter stations set out, or which are too deep to produce recognizable anomalies.

From the above it is clear that a gravimeter survey will not eliminate test drilling but it will greatly reduce the amount of drilling required to adequately test an area, by excluding from such testing the large proportion of the surveyed area which contains no significant anomalies. Furthermore, as mentioned above, the maximum significant drilling depth to test a gravity feature can be limited by the gravity survey data. Therefore, for prospecting of this kind, gravimeter work should be considered primarily useful for guiding and limiting exploratory drilling.

The gravimeter surveys in Cuba described in this paper can be considered to be only a sample. The area of the Camaguey chrome district is roughly 100,000 hectares (400 square miles) and the chromite production to date, plus unproduced known reserves of shipping grade ore, have been estimated[9] at 1,000,000 tons within 100 feet of the surface with a predicted additional 1,000,000 tons for each additional 100 feet of depth or an average of about 7,500 tons per sq. mile within a 300 foot depth. A gravimeter survey covering less than one square mile of this area and subsequent testing of most of the more favorable anomalies shown by that survey have increased the known ore reserves by a very considerable amount (of as yet unspecified grade) within a depth of about 300 feet. On the basis of the small area covered and the dispersion of the previously known deposits, it may be considered very fortunate that the gravimeter survey led to the discovery of any ore body of consequence at all. We must admit, of course, the possibility that the selection of the areas to be worked may have been a favorable factor. On the other hand, a possible and most attractive conclusion is that the chromite reserves of the district have been greatly under-estimated and that many important deposits remain to be discovered.

ACKNOWLEDGMENTS

The authors are deeply grateful to Mr. M. L. Jacobs, Vice President of the Bethlehem Steel Company, for permission to make public

[9] Thayer, *op. cit.*, pp. 27–31.

the gravity data and for supplying and releasing information on the findings of their core-drill testing of the gravity results. Also, we wish to express appreciation for courtesies, advice and assistance from Messrs. W. L. Cumings, Geologist, D. M. Fraser, Assistant Geologist and P. Telfair of the Bethlehem Steel Company and from Messrs. Joe Webb Peoples, T. P. Thayer, and H. E. Hawkes, Jr. of the United States Geological Survey.

The zealous and painstaking discharge of their duties by the personnel of the gravimeter party should not be overlooked as an important factor in the attainment of the unusually high precision required in the work. The party manager was one of the authors (W. K. Hastings); gravimeter operator. I. D. Dyer; surveyor, J. B. Rickets, and computer, T. R. Easterling, Jr.

Finally, we wish to thank Dr. P. D. Foote and Dr. E. A. Eckhardt of the Gulf Research & Development Company for permission to publish this paper.

ESTIMATING ORE MASSES IN GRAVITY PROSPECTING*

SIGMUND HAMMER†

ABSTRACT

The interpretation of the results of gravitational prospecting surveys is considered, from a theoretical point of view, in terms of the magnitude of the causative mass as distinct from the conventional interpretation in terms of the mass distribution (size, shape and depth). A general proof is given, based on Gauss' Theorem in potential theory, that the former problem is unique and the uniqueness is illustrated by an analytical example which also serves to demonstrate the well-known lack of uniqueness of the latter problem.

Practical formulae are presented for estimating the total mass directly from the gravity data and the precision of the mass estimate is considered. The method is applied to a practical gravimeter survey over a known chromite ore body and the estimated mass is found to be in excellent agreement with estimates from core drilling.

INTRODUCTION

Modern gravimeters and field techniques have been developed to the point that the possibility of success in prospecting for mineral ore deposits is becoming an actuality.[1,2,3,4,5] A desirable accompaniment of this instrumental development is the consideration of those aspects of the interpretational theory which pertain especially to prospecting for ore bodies. The interpretation of the results of gravity surveys is fundamentally the same whether the objectives are subsurface traps for petroleum or ore bodies, but there is one aspect which differs in the two cases, namely, the importance of determining the mass of an ore body which produces an observed gravity anomaly. The purpose of the present paper is to consider this problem. We hope to show that it is of fundamental as well as practical interest.

* Published by permission of the Gulf Research & Development Company, Pittsburgh, Pennsylvania. Read by title at the Fourteenth Annual Meeting, Dallas, Texas, March 21, 1944.

† Gulf Research & Development Company, Pittsburgh, Pennsylvania.

[1] Helmer Hedstrom, *A New Gravimeter for Ore Prospecting*, Trans. AIMME, Vol. 138, GEOPHYSICS 1940, pp. 235–257.

[2] C. A. Heiland, *Geophysics in War*, Colorado School of Mines Quarterly, Vol. 37, No. 1, pp. 61–84, Jan. 1942.

[3] Virgil E. Barnes and Frederick Romberg, *Gravity and Magnetic Observations on Iron Mountain Magnetite Deposit, Llano County, Texas*, GEOPHYSICS VIII, 1, pp. 32–45, January 1943.

[4] Mark C. Malamphy and James L. Vallely, *Geophysical Survey of the Arkansas Bauxite Region*, GEOPHYSICS IX, 3, pp. 324–366, July 1944.

[5] Sigmund Hammer, L. L. Nettleton and W. K. Hastings, *Gravimeter Prospecting for Chromite in Cuba*, GEOPHYSICS, X, 1, pp. 34–49, January 1945.

A gravitational survey in petroleum prospecting is usually considered to be evaluated completely when the observed anomalies have been interpreted in terms of the probable size and depth of associated subsurface geological structures. These interpretational factors are also of interest in prospecting for ore and the interpretational technique for evaluating these two factors[6] is fundamentally the same in the two cases. The mass of the subsurface structure which produces the observed gravity anomaly is of little interest in prospecting for petroleum and, therefore, it is not surprising that the interpretational technique for estimating the mass has received only scant attention[3] in the technical literature of applied geophysics.

THEORY—GAUSS' THEOREM

It is well known that the interpretation of gravitational (and magnetic) data in terms of structure is not unique and that geological considerations must be invoked to select the most probable interpretation out of the infinitely many which are theoretically possible.[7] This has been nicely illustrated by Tsuboi and Fuchida[8] by showing that the gravity anomaly

$$g(x) = g_0 e^{-x^2} \tag{1}$$

can be accounted for exactly (in the strict mathematical sense) by a surface density distribution

$$\sigma(y) = \frac{g_0}{2\gamma\pi^{3/2}} \int_0^\infty e^{\lambda z - \lambda^2/4} \cos \lambda y d\lambda \tag{2}$$

condensed on a plane at any depth Z. The various forms of this mass distribution at different depths are shown in Fig. 1. However, in the present paper, we are interested in the total mass in each of these various distributions and this may be found by integrating $\sigma(y)$ with respect to y from $-$ infinity to $+$ infinity. The result is*

[6] See, for example, L. L. Nettleton, *Gravity and Magnetic Calculations*, GEOPHYSICS VII, 3, pp. 293–310, July 1942.

[7] See, for example, L. L. Nettleton, *Geophysical Prospecting for Oil*, McGraw-Hill, First Edition, 1940, pp. 119–121.

[8] C. Tsuboi and T. Fuchida, *Relations between Gravity Values and Corresponding Subterranean Mass Distribution*, Bulletin of the Earthquake Research Institute, Tokyo Imperial University, Vol. XV, Part 3, pp. 636–649, September 1937.

* The integral was evaluated for the writer by Mr. Thomas A. Elkins of the Gulf Laboratories, making use of the Fourier Repeated Integral Theorem. (See Whittaker

$$M = \frac{g_0}{2\gamma\pi^{3/2}} \int_{-\infty}^{\infty} dy \int_0^{\infty} e^{\lambda z - \lambda^2/4} \cos \lambda y d\lambda = \frac{g_0}{2\gamma\pi^{1/2}} \cdot \qquad (3)$$

The significant feature of this result, for our present purpose, is that the total mass is independent of the depth Z; in other words, the various distributions shown in Fig. 1 all have the same total mass. This

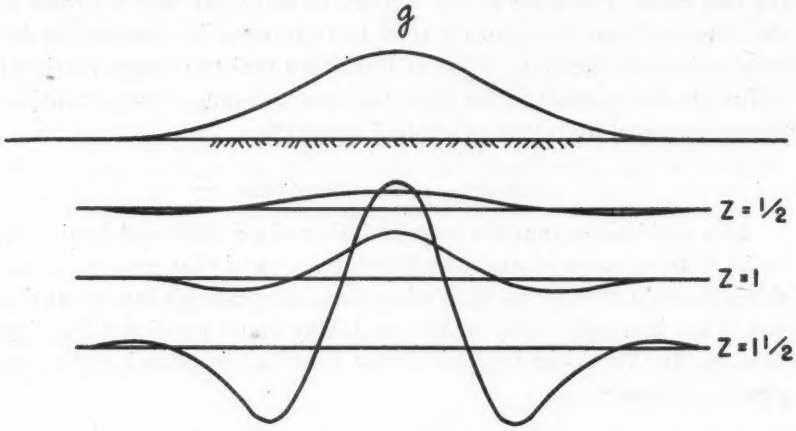


FIG. 1. Mass distributions with identical gravity effects. The ordinates of the curves below the surface are proportional to the surface density of the respective masses, condensed on the planes at the various depths. (After Tsuboi and Fuchida).

suggests that, unlike the lack of uniqueness of an interpreted mass *distribution*, the *magnitude* of the mass is determined uniquely by the gravity anomaly. We shall show that this suggestion is, in fact, true in general.

A very powerful tool of great generality for determining the magnitude of the mass producing a gravity anomaly is the classical Gauss' Theorem[9] of mathematical physics, which states that the total flux of the force of attraction over any closed surface in a gravitational (Newtonian-inverse square) field of force is equal to $4\pi\gamma$ times the total mass enclosed by the surface. In mathematical language

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and Watson, *A Course of Modern Analysis*, MacMillan, American Edition, 1943, p. 189).

[9] Gauss' Theorem is discussed in many books on Potential Theory. See, for example, A. S. Ramsey, *An Introduction to the Theory of Newtonian Attraction*, Cambridge University Press, First Edition, 1940, p. 71.

$$\int_S \int g_n dS = 4\pi\gamma M \qquad (4)$$

where g_n is the inward component of the gravitational attraction normal to the element (dS) of the surface and γ is the gravitational constant. The point we wish to emphasize in the present connection is that Eq. 4 is valid without restriction on the shape of the surface and on the distribution (size, position and shape) of the mass for any physical case which is likely to be of interest in geophysical problems. Thus, Gauss' Theorem gives a method of determining the magnitude of the anomalous mass producing a gravity anomaly directly from the gravity data without the necessity of assuming or calculating the form and depth of the mass anomaly. It seems strange that this well known Theorem has received so little attention in the literature of applied geophysics.*

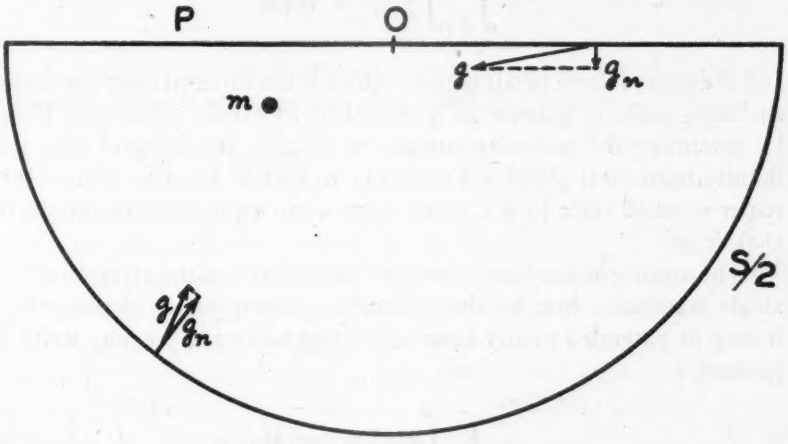

FIG. 2. Special case of Gauss' Theorem.

A special case of Gauss' Theorem applicable to determining the mass producing a gravity anomaly is indicated in Fig. 2. Gravity anomalies of interest in applied geophysics are generally sufficiently localized so that the level surface to which the "observed" Bouguer Anomaly gravity values are referred may be considered to be a plane.

* The only such published reference known to the writer is in a recent paper by Barnes and Romberg (*op. cit.*, page 45, Eq. 3) where an equivalent equation is given without reference or proof and, unfortunately, with a numerical factor 2 missing in the denominator.

The surface enclosing the attracting (anomalous) mass then may be chosen in the convenient form of a half sphere of infinite radius with the diametral plane (P) representing the level surface of the earth. We integrate the normal component of the gravitational attraction over the infinite plane P and it is not difficult to show, in the special case of a single mass point (m) located within a finite distance of the origin (O), that

$$\int_P \int g_n dS = 2\pi\gamma m \tag{5}$$

independent of the location of the mass point.

Similarly, the integral over the infinite half sphere S/2 is

$$\int_{S/2} \int g_n dS = 2\pi\gamma m$$

and the sum of these two integrals, which is the integral over the entire enclosing surface, is $4\pi\gamma m$ as it should be by Gauss' Theorem. Thus, by extending the enclosing surface to infinity, the integral over the infinite horizontal plane is a corollary to Gauss' Integral and in this paper we shall refer to Eq. 5 and subsequent equivalent equations in that sense.

The argument has been based, for simplicity, on the attraction of a single mass point but, by the principle of superposition of potentials, it may be extended to any finite attracting body and we may write in general

$$\int_P \int g_n dS = 2\pi\gamma M. \tag{6}$$

It may be instructive to point out that Eq. 6 may be derived simply by evaluating the integral over the infinite horizontal plane, and that the principal content of this paper could be based on Eq. 6 without reference to Gauss' Theorem. However, the writer feels that considering Eq. 6 as a corollary to Gauss' Theorem provides a well established theoretical background for the analysis and helps to clarify the concept we wish to emphasize.

If Δg represents a local gravity anomaly, Eq. 6 may be rewritten as a practical formula for determining the total anomalous mass which produces the anomaly, namely

$$\Delta M = \frac{1}{2\pi\gamma} \int_P \int \Delta g dS \tag{7}$$

where Δg is the value of the conventional gravity anomaly and the integration is to be carried out over the total horizontal extent of the anomaly. In other words, the magnitude of the anomalous mass is determined by the total "volume" under the gravity anomaly without any assumptions about the size, shape, depth and density contrast of the anomalous body other than the physically trivial restrictions involved in the proof of Gauss' Theorem.

If the anomalous body has a density σ_c enclosed in matter of density σ_s, the total mass of the body, which is the factor of interest in ore prospecting, is given by

$$M = \frac{1}{2\pi\gamma} \frac{\sigma_c}{\sigma_c - \sigma_s} \int_P \int \Delta g dS. \tag{8}$$

In the case of two-dimensional mass distributions in which the anomaly is very long compared to its width, Eq. 8 takes the form

$$M = \frac{1}{2\pi\gamma} \frac{\sigma_c}{\sigma_c - \sigma_s} \int_{-\infty}^{\infty} \Delta g dx \tag{9}$$

where now M is the mass per unit length.

We have seen in Fig. 1 that different mass distributions may produce identical gravity anomalies and, therefore, the uniqueness of the total mass calculated by Eqs. 7 to 9 must be investigated. A general proof of the uniqueness is as follows: Assume two mass distributions M and M' which produce identical gravity effects g_n and g_n' everywhere on the plane P in Fig. 2. Then by Eq. 6

$$\int_P \int g_n dS = 2\pi\gamma M$$

$$\int_P \int g_n' dS = 2\pi\gamma M'$$

independent of the distributions and depths of the two assumed masses. But, by hypothesis, $g_n = g_n'$ everywhere on the plane P and, therefore, the two integrals are equal. Therefore, the total mass of the two distributions must be equal.

These considerations show that the problem of determining the

distribution of the mass producing a gravity anomaly is fundamentally different from the problem of determining the *magnitude* of the total mass. The former problem is inherently not unique and a solution that may be obtained by any method must be subjected to the test of geologic reasonableness or other control before it can be accepted. The latter problem has a unique solution and, therefore, may be solved by direct methods with complete confidence that the result obtained is the correct one within the limitations of the data and practical imperfections in the calculations.

PRECISION OF MASS ESTIMATE BY GAUSS' THEOREM

To evaluate the utility of Gauss' Theorem in determining the mass of an anomalous body, such as an ore deposit, we must investigate the errors entailed in its use with practical data. There are three factors which should be considered: (1) the probable errors of the observed gravity values, (2) the closeness of spacing of the gravity stations and (3) the definiteness with which extraneous influences may be eliminated from the observed gravity anomaly under consideration. A complete study of the effect of all these factors has not been made by the writer. However, the following analytical considerations may serve to indicate the magnitude of the error which may occur.

A common type of error in an observed gravity anomaly is that the far flanks are obscured by errors in the data and by extraneous influences so that the full horizontal extent of the anomaly is not recognizable. The situation is suggested by diagram A of Fig. 3, in which the "true" anomaly is indicated by a solid line and the "recognized" anomaly is shown by a dotted line. The difference between the two is called an error in "tailing off." The error in the mass estimate due to "tailing off" may be simulated for assumed simple geometrical mass forms by integrating the true gravity anomaly, not to infinity, but out to a point where the "volume" is equal to that of the recognized anomaly. We define the "error in tailing off" (g_e) as the ordinate of the true gravity value at that point. (See diagram A in Fig. 3.) It is convenient to express the "error" as a fraction of the maximum (true) gravity value (g_{max}) by the relation

$$e = g_e/g_{max}. \tag{10}$$

The application of Gauss' Theorem (Eq. 6) to the gravity anomaly with such an error in "tailing off" gives an estimated mass M' as follows:

For a mass point (spherical mass)

$$M' = M(1 - e^{1/3}). \tag{11}$$

For an infinite horizontal line element (cylindrical mass)

$$M' = M(2/\pi)\cos^{-1}e^{1/2} \tag{12}$$

where M is the true mass and e is the fractional error in the gravity

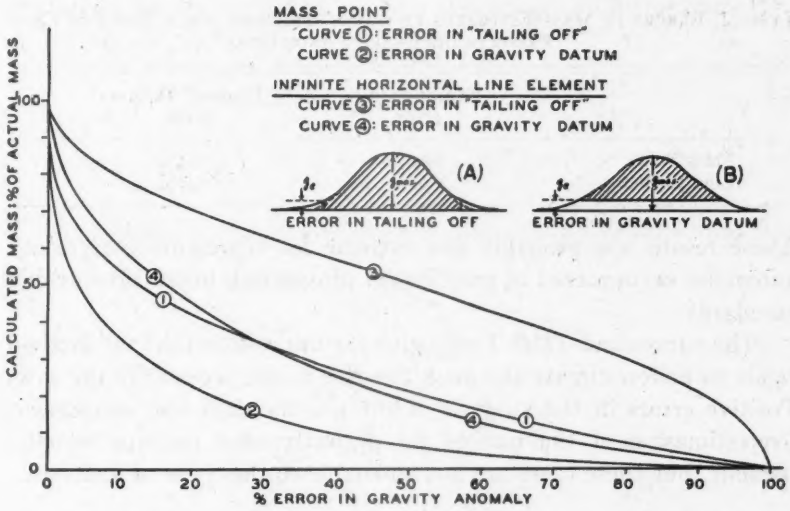

FIG. 3. Effect of errors in gravity data on mass estimation by Gauss' Theorem. ("Error in Gravity Anomaly" $= g_e/g_{max.}$)

anomaly, as defined by Eq. 10 above. The variation of M' as a function of e is shown for these two cases as curves (1) and (3) respectively in Fig. 3.

Another common type of error in the evaluation of a gravity anomaly is incorrect determination of the regional gravity datum. The situation and analysis in this case is similar to that above and should be obvious from diagram B in Fig. 3. The resultant equations are:

For a mass point

$$M' = M\{1 - (3/2)e^{1/3} + (1/2)e\}. \tag{13}$$

For an infinite horizontal line element

$$M' = M(2/\pi)\{\cos^{-1} e^{1/2} - (e - e^2)^{1/2}\} \tag{14}$$

which are plotted as curves (2) and (4) respectively in Fig. 3.

It is evident from these curves that large errors may occur in estimating the causative anomalous mass* by application of Gauss' Theorem to observed gravity anomalies with their inevitable observational errors and extraneous influences. Thus, from the curves in Fig. 3, a ten per cent error in the gravity anomaly (in the sense of the rather arbitrary definitions used here) results in errors in the estimated masses, as shown in Table I.

TABLE I. ERRORS IN MASS ESTIMATES BY GAUSS' THEOREM FOR A TEN PER CENT ERROR IN THE GRAVITY ANOMALY

	"Tailing Off" error	Regional Datum error
Mass Point	−47%	−65%
Line Element	−21%	−40%

These results are probably not extreme for representative gravity anomalies encountered in geophysical prospecting under present-day standards.

The curves and Table I may give the impression that the method tends to underestimate the mass but this is not necessarily the case. Positive errors in the analysis of the gravity data and consequent overestimation of the masses are perfectly, and perhaps equally, possible, but these cases are not amenable to this type of analysis.

OTHER METHODS OF MASS ESTIMATION

The causative mass may be estimated from the gravity anomaly by assuming that the attracting body has a simple geometrical form. In the simpler cases, the method consists essentially of estimating the depth of an assumed body from the width of the gravity anomaly and then calculating the mass anomaly in terms of the maximum gravity value of the anomaly and the estimated depth of the body.

For a spherical mass (See Fig. 4), the depth to the center (Z) is related to the "half-width" ($X_{1/2}$) of the gravity anomaly† by the relation

* The determination of the total mass requires knowledge or assumptions as to the actual densities involved, which introduces another possible factor of error. The determination of the anomalous mass by Gauss' Theorem is not dependent on any such assumption and, therefore, is free from this uncertainty.

† The "half-width" is the horizontal distance from the center of the anomaly out to the point where the anomalous gravity value has decreased to one-half the amplitude at the center.

$$Z = 1.305x_{1/2} \tag{15}$$

and the mass anomaly and mass respectively are given by

$$\Delta M = Z^2 g_{max}/\gamma \tag{16}$$

$$M = \frac{\sigma_c}{\gamma(\sigma_c - \sigma_s)} Z^2 g_{max}. \tag{17}$$

For an infinite horizontal cylinder the corresponding formulae are

$$Z = x_{1/2} \tag{18}$$

$$\Delta M = Z g_{max}/2\gamma \tag{19}$$

$$M = \frac{\sigma_c}{2\gamma(\sigma_c - \sigma_s)} Z g_{max}. \tag{20}$$

If the shape of the gravity anomaly departs appreciably from that

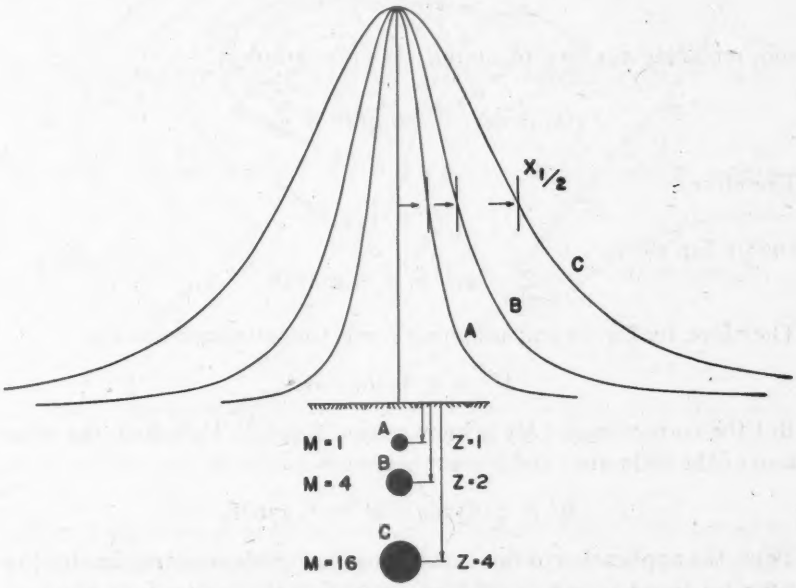

FIG. 4. Gravity effects of spherical masses at various depths. $X_{1/2}$ is the "half-width" of the gravity profile.

for the assumed sphere or cylinder, these formulae will not yield precise results, as they depend on fitting the gravity profile at only two points, namely, at the maximum and half-width. More elaborate for-

mulae based, for example, on the area of the gravity profile out to any selected distance from the origin are easily derived but such formulae are probably not in general use.

More complicated geometrical forms have been used, such as vertical cylinders, vertical laminae and rectangular bodies.[3] These cases involve a combination of estimation and calculation to determine the dimensions of the body to fit the observed gravity anomaly.

All such methods suffer from the lack of uniqueness of the assumed mass distribution and, of course, depend upon the degree to which the calculations are carried to fit all points of the observed gravity anomaly.

We can test this type of method on Tsuboi and Fuchida's problem discussed above. Since their mass distribution is two-dimensional, we will utilize the infinite horizontal line element to estimate the mass associated with the gravity effect. Eq. 1 gives

$$g_{max} = g(0) = g_0$$

and, replacing $x_{1/2}$ by d to simplify the typography

$$g(x_{1/2}) \equiv \frac{g_{max}}{2} \equiv g(d) = g_0 e^{-d^2}.$$

Therefore,

$$e^{-d^2} = 1/2$$

and by Eq. 18

$$Z = x_{1/2} \equiv d = 0.8326.$$

Therefore, by Eq. 20 and assuming $\sigma_s = o$, the estimated mass is

$$M' = 0.8326 g_0 / 2\gamma.$$

But the correct mass (M) is known from Eq. (3). Therefore, the relation of the estimated and correct masses is

$$M' = 0.8326\pi^{1/2} M = 1.476M.$$

Thus, the application of this method to this problem overestimates the mass by about 50 per cent.* The overestimation arises from the fact

* It may be of interest to point out that the application of Gauss' Theorem in the appropriate form, Eq. 9, to this problem, and assuming $\sigma_s = 0$, gives the mass

$$M = \frac{1}{2\pi\gamma} \int_{-\infty}^{\infty} g_n dx = \frac{g_0}{\pi\gamma} \int_0^{\infty} e^{-x^2} dx = \frac{g_0}{2\gamma\pi^{1/2}}$$

which, as of course it must, agrees with the result in Eq. 3 obtained by direct integration of the mass distribution.

that the gravity effect of the "equivalent" horizontal line element becomes much greater than $g_0 e^{-x^2}$ beyond the half-width point at which the two gravity curves intersect.

PRACTICAL APPLICATION OF GAUSS' THEOREM

The gravimeter survey over a chromite ore body which has been closely delimited by core drilling is mapped in Fig. 5. This has been derived from Fig. 1 in another paper[5] by the removal of an estimated regional gravity effect. For the purpose of applying Gauss' Theorem to

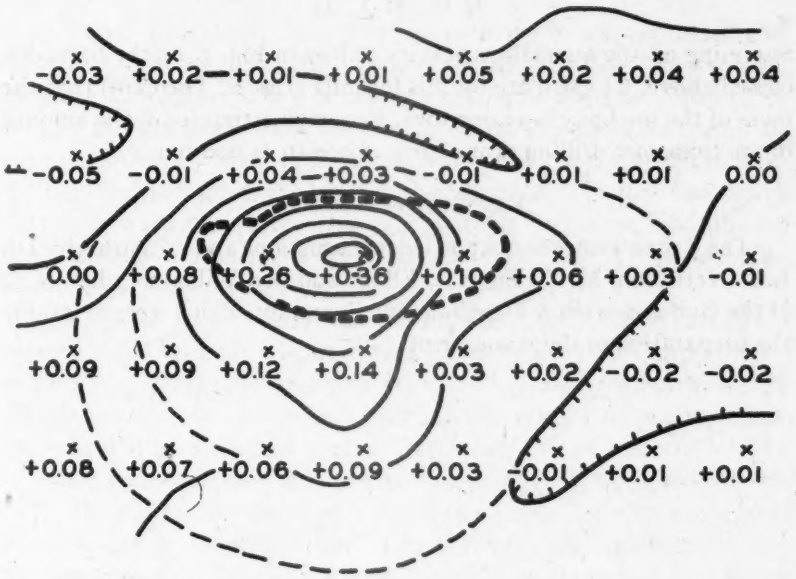

FIG. 5. Gravimeter results over a known chromite ore body. Gravimeter values are in milligals and station spacing is 20 meters. The heavy dashed line is the outline of the ore body from test drilling.

estimate the mass of the local ore body, some extraneous influences, especially in the lower left part of the map, have been inferred, as indicated by the dashed gravity contours. Where these dashed contours depart from the station values, the gravity effect of the known ore body is assumed to be given by the dashed contours. At other points, the gravity effect of the ore body is considered to be the station value.

Approximating the integral in Eq. 8 by a summation over the discrete gravity station points and introducing numerical factors, we obtain the practical formula

$$M = 0.2634 \frac{\sigma_c}{\sigma_c - \sigma_s} \sum \Delta g \cdot S^2 \qquad (21)$$

where M is the total mass in (2000 pound) tons, Δg is the anomalous gravity value in 1/100 mg units and S^2 is the area in square meters associated with each gravity station point. For a regular square array of stations with twenty meter spacing and taking the densities[5] of the chrome ore and of the country rock to be 4.0 and 2.5, respectively, Eq. 21 reduces to

$$M = 281 \sum \Delta g.$$

Summing up the anomalous gravity values in Fig. 5, on the basis discussed above, we calculate by this formula (Gauss' Theorem) that the mass of the ore body is 40,000 tons. Reported estimates of the amount of ore from core drilling range from 28,000 to 44,000 tons.

ACKNOWLEDGMENT

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WORKING DEPTHS FOR LOW FREQUENCY ELECTRICAL PROSPECTING*

WILLIAM BRADLEY LEWIS†

ABSTRACT

Electrical measurements were made on the surface of the earth with low frequency commutated current using nineteen separate frequencies and six electrode separations. Analysis of the data indicates that there is an effect of appreciable magnitude attributable to an interface 6000 feet below the surface.

INTRODUCTION

A proof that surface electrical measurements are appreciably affected by resistivity changes several thousand feet below the surface is of great importance. Such a proof would show the possibility of detecting oil and gas *in situ*, for the measurements are affected by the most significantly diagnostic property of petroleum, its high resistivity.[1] It would afford to exploration the possibility of a new and powerful tool, not only supplementing existing tools—which at best dilineate structures favorable for petroleum accumulation—but going a step further, and working directly on the petroleum itself.

This proof will be based on experiment. The implications of the experimental findings will be discussed in broad terms appealing to physical intuition and common sense rather than to mathematics. When recourse to theory is required, the results of mathematical analysis will be presented without derivation.

Measurements were made with low frequency commutated current. The current consisted of a series of alternating pulses separated by intervals of no current flow. The potential was measured during the gap intervals. The gap interval was, at all frequencies, of about 35% greater duration than either the pulse interval or the measuring interval. Measurements were made at 19 frequencies ranging from 0.3 to 1.3 cycles per sec.

APPARATUS

Fig. 1 shows a schematic diagram of the apparatus. The commutating switches in the current circuit and potential circuit are motor driven, operating synchronously but 90 degrees out of phase, and so

* Presented at the fourteenth annual meeting, Dallas, Texas, March 1944.

† The Elflex Company, Houston, Texas.

[1] The diagnostic value of electrical measurements for determining quantitatively the oil saturation of sand cores in the laboratory has been long appreciated. See Wyckoff and Botset: *Physics* (1936) 7, 325; Leverett: *Trans. A.I.M.E.* (1939) *132*, 149.

adjusted that the contact interval was less by the desired amount than the no-contact interval. A coupling, consisting of an impedance network, coupled by an air core transformer to the earth current circuit, supplies a measuring potential across the potentiometer in the potential circuit. This potential is proportional to the earth current. A bucking circuit is used to eliminate potentials due to natural earth currents.

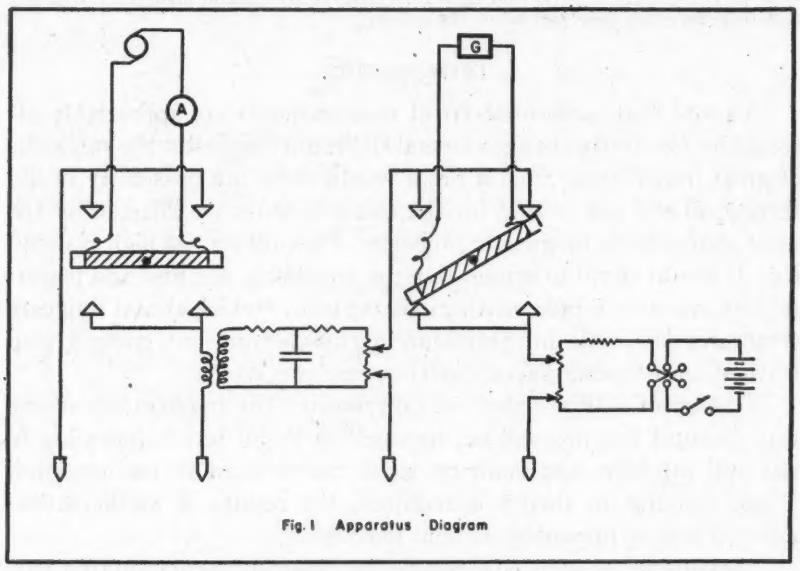

FIG. 1. Schematic diagram of apparatus. Shown are current commutator, current-potential coupling circuit, potentiometer, potential commutator, 90° out of phase with current commutator, galvanometer, and natural earth current bucking circuit.

When a null balance is indicated by the galvanometer, the slide wire reading of the measuring potentiometer indicates a potential per unit current in arbitrary units. The galvanometer is a Leeds and Northrup #2420-C, with a sensitivity of 2.5×10^{-8} amps per mm. The scale can be read to about 1/40 mm.

Fig. 2 shows the frequency response of the coupling. This gives the output of the coupling in microvolts per slide wire division per ampere as a function of frequency. The calibration was checked daily for several months and proved constant within the accuracy of the measurements. This curve is used to convert experimental readings from arbitrary units to microvolts per ampere.

GENERAL DISCUSSION

Before going into experimental details it will be well to examine the procedure in general and ascertain what sort of information can be obtained from measurements of this nature.

It is a well known result of electromagnetic theory that when a current is periodically reversed in a continuous medium, electromagnetic waves are created. Energy is transmitted through the medium

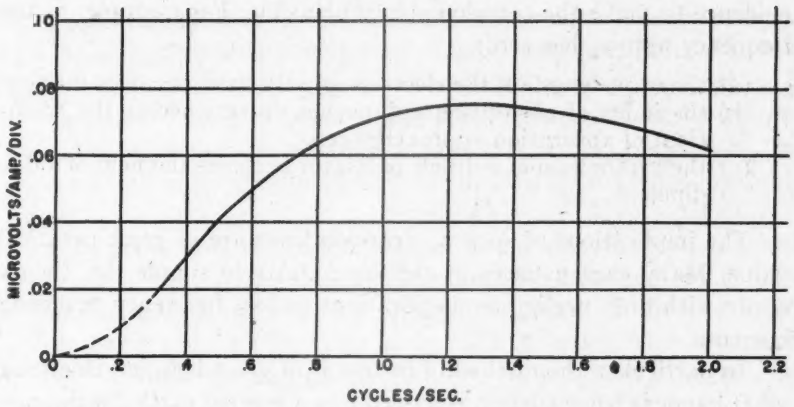

FIG. 2. Frequency response curve of the coupling circuit, giving microvolts output per potentiometer scale division, per ampere ground current, as a function of frequency.

by these waves. Their behavior is fully described in Maxwell's treatment of the problem.

Certain results of Maxwell's theory will be used without further elaboration and without derivation. These results will be taken from the plane wave solution of the differential equation and from the dipole oscillator solution.

The first will give the relations between speed of propagation, wave length, and index of absorption, and the parameters: frequency, resistivity, dielectric constant, and magnetic permeability.

The second will give the dispersive characteristics of the medium for waves generated by a dipole oscillator.

CORRESPONDENCE PRINCIPLE

The frequencies employed in this work are low compared to those used in many branches of electrical work, but it should be emphasized that any differences in the results obtained using these low fre-

quencies must be only differences in degree, not in kind. Furthermore, as the frequency is decreased toward zero frequency, the response of the system to the electrical excitation must approach its response to direct current. The direct current response may be considered the limit approached asymptotically as the frequency is decreased.

A correspondence can be made between the direct current case, and the case of very low frequency currents. No attempt has been made to establish this correspondence with perfect rigor, but there is sufficient evidence to make the correspondence plausible. For example, as the frequency approaches zero:

(a) the wave length of the electromagnetic wave becomes infinite;
(b) the index of absorption approaches unity whereas the coefficient of absorption approaches zero;
(c) the vector field of a dipole oscillator becomes the field of a d.c. dipole.

The implications of such a correspondence are of great practical value. Many consequences of the comparatively simple d.c. theory apply with only negligible modifications to low frequency reversing currents.

In particular, the method of images is of great help in visualizing what happens when current is passed into a layered earth. In the case of direct current, the nature of images has been exhaustively treated.[2] At any surface of discontinuity the divergence of the current does not vanish. Instead, a charge accumulates on the surface. The surface distribution of this charge is such as to produce the same effect as would obtain from an image source. Thus the image has the same sort of physical reality, and is as effective in producing a potential, as the source where current flows into the earth.

For slowly changing currents it is permissible to assume that the charge on the surface of discontinuity is always at its static equilibrium value. This is effectively the same as assuming that the images change synchronously with the sources. As long as this assumption is valid, the convenience of the image method can be extended from the d.c. case to the case of periodically reversed currents.

From the other aspect of the correspondence, electromagnetic waves thought of as originating from the image sources, undergo absorption as prescribed by Maxwell's theory. The reduction in amplitude of the wave due to absorption is an exponential function of the

[2] H. M. Evjen: GEOPHYSICS III, 2, 78.

length of path travelled. If this distance is measured in terms of the wave length of the electromagnetic waves, the index of absorption is used. This index is unity for a medium such as the earth for frequencies less than 10,000 cycles per second. It is at once evident, that the effect of deep images is obliterated by absorption as the frequency is increased.

GEOMETRIC SIMPLIFICATION

Another simplifying assumption that will be used in this discussion is geometric, viz: that the dipole is a fair approximation to the finite double-pole. The actual conditions of experiment deal with a source and a sink separated a finite distance. These may be replaced by a dipole source having the same strength and orientation as the double-pole. By using the correspondence principle, we may appeal to the d.c. case, for which the dipole- and double-pole fields are readily computed.

In what follows the terms "image" and "reflection" will be used frequently. The former will have the meaning described above. The latter will usually refer to the observed anomaly in the dispersion graph that is associated with an image. This is analogous to the use of "reflection" in seismology when referring to a characteristic pattern on a seismic record.

The guiding philosophy behind this experimental work has been presented previously.[3] The present work was designed to show unmistakably that certain effects observed by means of surface electrical measurements can not be attributed to shallow causes and can be readily explained as having their origin in deep images.

Such a demonstration must appeal directly to physical intuition. It is desirable that the proof be as direct, and with as little interposition of mathematical manipulation as is possible.

It was thought this could best be accomplished by means of an expansion whereby the electrode separation was kept constant for the current pair and the potential pair, but the distance between the two pairs was varied. By this means, direct and shallow effects should drop off rapidly as the separation was increased, whereas effects attributable to deep images would remain comparatively constant.

A line was chosen just north of the town of Hockley, Harris County, Texas, in an area that had previously been explored. The choice of this line was based on the uniformity of the previously ob-

[3] H. M. Evjen: GEOPHYSICS VII, 2, 146.

served stations, indicating that there were no violent changes in the electrical properties of the ground in the region covered by the expansion. In other words, the ground in this region is a fair representative sample of a stratified earth, not complicated by faulting or other structural anomalies.

EXPANSION EXPERIMENT

Six runs were made in which the spacing between the centers of the two electrode spreads was varied by equal increments from one run to

TABLE I. EXPERIMENTAL DATA

The negative of the observed microvolts per ampere is tabulated for each separation and each frequency. The factor for converting the observed slide wire reading to microvolts per ampere is tabulated in the second column.

Frequency cycles/sec.	Coupling factor microvolts/amp./div.	Double-pole separation in 750 ft. units					
		5	7	9	11	13	15
.30	.0175	2.00	1.28	1.07	.75	.61	.18
.34	.0230	2.32	1.52	1.15	.83	.55	.16
.38	.0276	2.37	1.57	1.08	.77	.39	.14
.42	.0325	2.54	1.50	1.01	.62	.33	.10
.46	.0368	2.64	1.57	.99	.44	.18	.05
.50	.0410	2.58	1.47	.90	.37	.16	.00
.55	.0455	2.59	1.46	.82	.27	.14	−.09
.60	.0500	2.65	1.60	.75	.20	.05	−.20
.65	.0540	2.80	1.62	.70	.16	−.05	−.27
.70	.0575	2.82	1.67	.69	.06	−.06	−.40
.75	.0608	3.04	1.88	.67	.06	−.18	−.32
.80	.0635	3.17	1.78	.83	.13	−.25	−.32
.85	.0662	3.51	1.92	1.06	.20	−.06	−.20
.90	.0685	3.70	2.19	1.23	.27	.00	−.13
.95	.0702	3.86	2.46	1.40	.35	.00	−.07
1.00	.0718	4.09	2.44	1.44	.50	.14	−.07
1.10	.0739	4.44	2.66	1.70	.67	.22	.00
1.20	.0748	4.78	2.84	1.87	.97	.45	.00
1.30	.0750	5.25	2.85	2.02	1.12	.45	.00

the next. The four electrodes lay in a straight line. In each run measurements were made at 19 frequencies distributed from 0.30 to 1.30 cycles per sec. The current in all runs was about 1.3 amperes.

The observed slide wire settings were converted to microvolts per ampere by means of the coupling factor shown in Fig. 2. Table I gives the observational data converted into microvolts per ampere as well as the conversion factor for each frequency. These data are shown graphically in Fig. 3. Each curve represents the observed response plotted against frequency for the indicated separation. The electrode

configuration is shown below the curves. The unit of length, A, is 750 feet. It will be noted that all of the curves are extrapolated to the origin. This point, though not observed, belongs on each curve, for the imaginary component of the potential vanishes for a current of zero frequency.

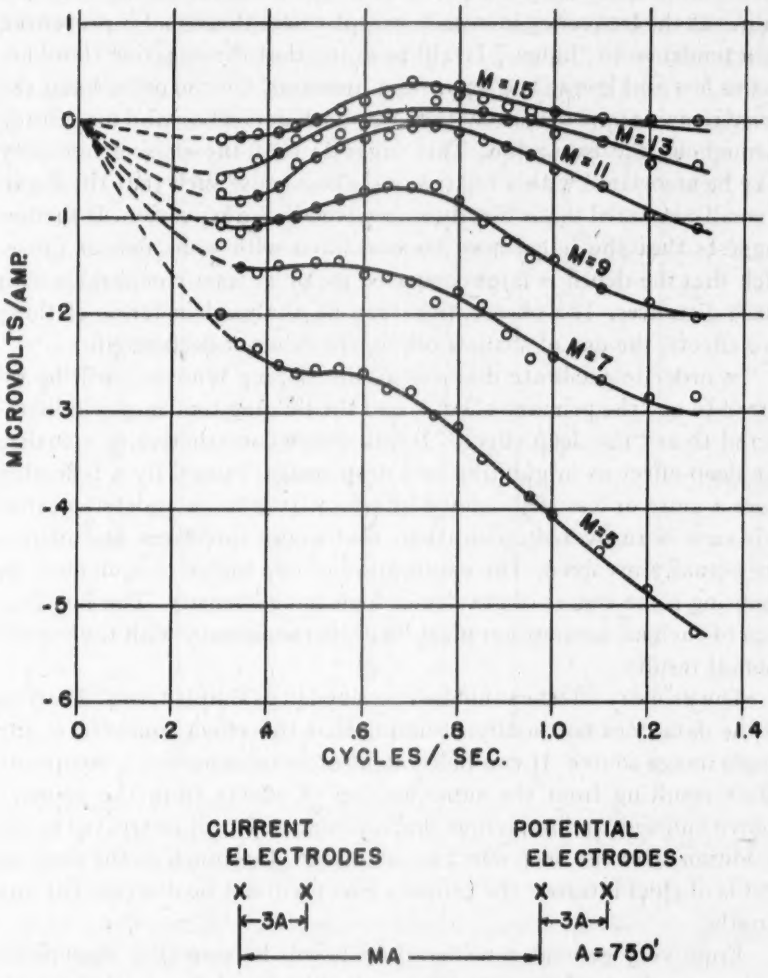

FIG. 3. Expansion data, showing magnitude of quadrature component of voltage per unit of current, as a function of frequency and separation MA between current and potential probes.

DISCUSSION

Certain broad features of these curves can be discussed without recourse to detailed analysis. Each curve exhibits increasing negative values as the frequency increases, except where this trend is prevented by a tendency to "bulge." It will be noted that the negative trend becomes less and less as the separation increases. On the other hand the bulge remains approximately the same both in position and magnitude throughout the expansion. This suggests that the sloping tendency may be associated with a relatively shallow cause such that the depth is small compared to the distances involved in the expansion. It further suggests that the bulge may be associated with some deeper cause, such that the depth is large compared to, or at least comparable with these distances. The observations can be analyzed in terms of these two effects, the one of shallow origin, the other of deep origin.

In order to facilitate discussion, the sloping tendency will be referred to as "the primary effect," and the bulging tendency will be referred to as "the deep effect." It will prove constructive to visualize the deep effect as originating in a deep image, caused by a reflection from a more or less well defined interface. It is to be understood that this view is an over-simplification, that many interfaces and images are actually involved. The assumption of one image is equivalent to choosing some center of gravity of high image density. The justification of such an assumption must lie in its consistency with the experimental results.

The primary effect cannot be described in as simple terms. Analysis of the data does not justify assuming that this effect comes from any single image source. It can be thought of as representing a composite effect resulting from the superposition of effects from the primary source and sink and numerous shallow images. It will be treated as the residuum after the deep effect is eliminated. Inasmuch as the deep effect is of chief interest, the primary effect will not be discussed at any length.

From very general considerations it will be seen that shallow effects must drop off very rapidly as the distance between the current and potential double-poles is increased. This is readily verified by considering the d.c. dipole. On the other hand, the effect caused by a deep image will be more or less constant, since there is a relatively small change in the distances involved.

We observe that the deep effect is practically constant over the expansion and that the primary effect does decrease rapidly. Then, if for

each frequency observed, we plot the observed effect against the reciprocal of the separation, we will find that we can extrapolate the curve to $1/x=0$. This extrapolated value gives the portion of the observed effect attributable to the deep image, on the basis of the above considerations. Having gone through this process for each frequency, the dispersion graph of the deep effect can be constructed.

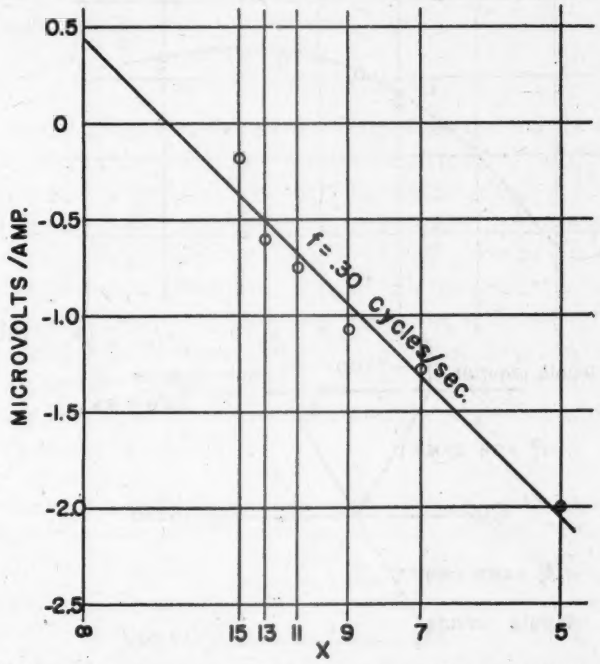

FIG. 4. Plot of quadrature component of voltage per unit of current at 0.3 cps, as a function of the reciprocal of the separation of the double-poles. The magnitude of the deep effect is obtained by extrapolation to $x=\infty$.

The experimental points when plotted against the reciprocal separation were found to be so nearly on a straight line that the extrapolated value was obtained by a least square calculation. This was done to eliminate any personal factor that might enter into graphical treatment. With the exception of the point corresponding to the highest frequency, the least square calculations are completely satisfactory. At high frequencies, however, there is reason to believe that values so obtained are somewhat too high. Examination of the data of Table I will show this.

Fig. 4 shows the method of constructing the deep effect. Only one frequency, .30 cycles per second, is plotted. The other frequencies give the same type of linear fit to the observational points.

The extrapolated values are given in Table II. These values are plotted in Fig. 5. The smooth curve drawn through the experimental

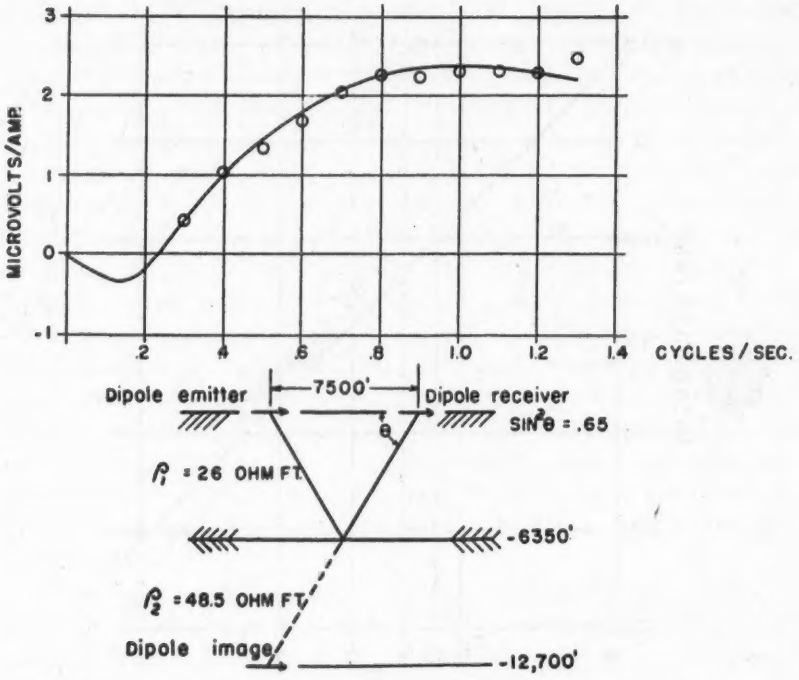

FIG. 5. The circles are the observed values of the deep effect potential per unit current, as a function of frequency. The solid line curve is the predicted deep effect potential, calculated from dipole theory applied to an earth of the characteristics shown.

points is the theoretical dispersion curve of a dipole oscillator which will be discussed later.

The fact that any reasonable curve can be obtained by this process justifies the working hypothesis and substantiates assigning the effect to a deep cause. Unless such an effect were produced by a cause originating at a depth of the same order of magnitude as the increment in the horizontal distance over the expansion, it could not, on any reasonable hypothesis, remain practically constant over the expansion.

That it does remain constant, is attested by the experimental curves themselves, and by the method of computing the deep effect.

It now remains to compute quantitatively what depth may be assigned to the deep effect. Up to this point, no theory has been called on other than broad intuitive considerations that apply quite generally.

The calculations of depth will be based on a comparison of the experimentally found dispersion curve of the deep effect, with the theoretical dispersion curve of a dipole oscillator.

CALCULATIONS OF DEPTH

The depth calculation requires certain assumptions. It has been demonstrated that we can attribute the deep effect to deep images of the primary source and sink. As these images are deep, their double-pole field can be closely approximated by a dipole field. Consequently the use of a dipole model is justifiable. Theory permits one to calculate the field of a dipole oscillator. This field is conveniently broken up into components: real and imaginary from the point of phase; and radial and tangential from the point of view of geometry. In this work, only the imaginary component is used, and the two geometric components are combined to secure a horizontal component which gives the best fit to the data.

TABLE II. OBSERVED DEEP EFFECT AND THEORETICAL VALUES FOR DIPOLE OSCILLATOR

Frequency cycles/sec.	Observed microvolts/amp.	Theoretical microvolts/amp.
.00	—	.00
.10	—	−.55
.20	—	−.47
30	.44	.44
.40	1.03	1.00
.50	1.34	1.45
.60	1.67	1.78
.70	2.03	2.02
.80	2.25	2.21
.90	2.24	2.35
1.00	2.30	2.37
1.10	2.30	2.31
1.20	2.30	2.25
1.30	2.47	2.21

The theoretical dipole dispersion curve appears in Fig. 5. This corresponds to a geometric scheme shown in the same figure. The depth was derived from the following considerations.

(1) The emitter-receiver separation for the deep effect dispersion curve was taken as 10 units, the mean separation for the expansion.

(2) The experimental points were found to fit most closely the theoretical curve for $\sin^2 \theta = .65$.

These considerations give the depth to the image to be 12,700 feet.

It is now possible to compute the effective resistivity of the earth. This computation gives the resistivity of a homogeneous medium that would give the observed effect, assuming the calculated geometric configuration.

This calculation involves knowledge of the frequency corresponding to any chosen point on the theoretical dispersion curve. The theoretical curve is a function of the numerical distance,[4] which is a dimensionless ratio involving distance, frequency, and resistivity. We know the frequency, have computed the distance geometrically, and can therefore compute the resistivity.

The result of such a calculation gives an effective resistivity of 26 ohm feet, with a change to 48 ohm feet at the reflecting interface. The effective resistivity is not at all out of line with what may be calculated from Schlumberger logs by averaging the resistivity from the surface to a depth of 6000 feet.

These reasonable values of computed resistivity are gratifying, for they serve to round out the experiment, giving a self-consistent picture quite in line with known conditions in the Gulf Coast.

APPENDIX

The problem of a dipole oscillator in empty space has been treated frequently *cf.* Page: *Theoretical Physics*. The more general problem of the dipole oscillator in a conducting medium was investigated by Sommerfeld. Sommerfeld's treatment has formed the basis for considerable theoretical work on the mutual impedance of grounded cables.[5] For the present problem, the dipole oscillator furnishes a more satisfactory model than the more complicated case of the grounded cables.

The radial and tangential imaginary components of the electric field of a dipole oscillator in a medium of resistivity ρ are given by:

[4] F. Ollendorff, *Erdstrome*. Chapt. VIII *et seq.*

[5] R. M. Foster. *Bell System Technical Journal*, *10*, 408 (1931).
Alfred Wolf. GEOPHYSICS, Vol. VII, no. 4, p. 414 (1942).
S. S. West. GEOPHYSICS, Vol. VIII, no. 2, p. 157 (1943).

$$E_r^j = \frac{2\rho \cos\theta}{r^3} e^{-\xi}[(1 + \xi) \sin\xi - \xi \cos\xi]$$

$$E_\theta^j = \frac{\rho \sin\theta}{r^3} e^{-\xi}[(1 + \xi) \sin\xi - (1 + 2\xi)\xi \cos\xi].$$

Where ξ is Ollendorff's numerical distance and θ is the polar angle.

The numerical distance is given by

$$\xi = 1.097\left(\frac{r}{1000}\right)(f/\rho)^{1/2}$$

where f is the frequency in cycles per second,

r is the radial distance in feet,

ρ is the resistivity in ohm feet.

Since we are concerned with the component of the electric field in the x direction we must consider

$$E_x^j = \sin\theta E_\theta^j - \cos\theta E_r^j.$$

By plotting E_x^j as a function of ξ^2 for various values of θ, the curve may be chosen that most closely fits the observational data.

ACKNOWLEDGMENTS

The author wishes to thank Dr. H. M. Evjen for his many constructive criticisms, and helpful suggestions both in outlining the experiment and in organizing this presentation of the findings. The author also wishes to express his appreciation to Mr. W. V. Mills for his help with calculations, and for drafting the several figures.

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APPLICATION OF MUD ANALYSIS LOGGING*

ROBERT E. SOUTHER†

ABSTRACT

The mud analysis logging system, now widely used for exploratory and routine drilling, continuously analyzes and records the oil and gas content of mud returns from wells being drilled by the rotary method. Oil or gas detected in the returning drilling fluid indicates oil or gas in the formation penetrated by the bit. Results of the continuous analyses are instrumentally correlated to the depths and formations from which the showings originated. A second useful phase of the system plots accurately and in detail rate of penetration or drilling speed on the log as a function of depth.

Trucks and trailers provide a mobile housing for all of the mud analysis equipment so that it may be moved rapidly from well to well.

Applications of the method may be divided into two classes:

1. Routine drilling in proved areas where it eliminates unnecessary coring, and locates gas caps and completion zones.
2. Exploratory drilling in which it minimizes coring by indicating for testing purposes porous zones containing oil and/or gas.

Mud analysis logging can be practiced in areas where the electrical log cannot be used due to high salt content or other local conditions, where dangerous hole conditions make interruption of drilling operations for coring inadvisable, and for evaluating gas zones where cores are difficult to interpret.

In addition, each mud analysis logging unit contains equipment to obtain information useful in eliminating washouts, in predicting and preventing blowouts, and in controlling drilling mud characteristics.

Mud analysis logging of drilling wells for the purpose of identifying oil and gas bearing formations has now been applied under a great variety of conditions. Definite techniques in the application and in the interpretation of results of mud analysis logging have developed out of this experience. This method has been applied in thirteen oil producing states, as well as in foreign countries. In this country, mud analysis logging has been in use for over five years and has more than forty discoveries and new pay zones to its credit.

A brief discussion of the equipment and methods employed in obtaining this information is essential to a thorough understanding of the techniques of applying the mud analysis logging principle.

The basis of this logging method is that as drilling progresses, the bit disintegrates a cylindrical section of the formation. A part of any oil or gas contained in the pore spaces of the formation penetrated will be entrained in the drilling mud and circulated to the surface. Continuous testing of the mud at the surface reveals the presence of the oil or gas and correlates these findings with the depths from which they originated.

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Electrical and fluoroscopic instruments developed for this particular application continuously analyze the drilling mud for its oil and gas content. For the purpose of detecting oil in the drilling mud, an ultra-violet light is used. The apparatus is capable of detecting quantities as small as one part of oil in a hundred thousand parts of mud. The device consists of a specially designed viewing box with a source of ultra-violet light and includes a magnifying glass and facilities for flooding the sample with visible light. The mud samples are treated to remove any excessive viscosity and gel strength before they are viewed in the detection apparatus. The oil in the samples appears as small bright spots under the ultra-violet light. By observing a fluorescent spot through the magnifier and then switching to visible light it is possible to distinguish crude oil from other oils or greases that may accidently get into the mud. It is surprising but fortunate that crude oil from a previous show that has already been around the system once or more is easily distinguished from a new show as the new oil fluoresces more brightly than that which has been circulated.

The analysis of the gas content of the drilling mud is accomplished by passing a portion of the returning mud through a gas trap where the gas is removed from the mud. A motor-driven vacuum pump constantly draws air through the trap and thence through a flexible hose to the analyzer where it passes in turn through a filter, a humidifier, a flow meter, and a "hot wire" gas detector. In order that the results of the oil and gas analysis may be correlated with depth, an instrument has been developed which indicates, as drilling progresses, the depth of the bit at all times. This entirely automatic instrument reads directly in feet. A second instrument continuously gives the operator the depth from which any oil or gas indicated by the analysis entered the mud stream even though, at the time of the analysis, the bit may have penetrated a few additional feet.

A third instrument, working in conjunction with the instrument showing the depth of the bit, plots against depth an accurate and detailed rate-of-penetration curve. Rate-of-penetration curves are being found increasingly useful in all types of drilling operations. These curves are used as an indication of porosity and permeability and as an indication of changing formations. Drilling rate curves are also useful in correlation between wells in the same general area. Rate-of-penetration, when correlated with bit records, gives excellent information to be used in planning bit programs.[1]

[1] J. T. Hayward and L. M. Swift, *Instruments for "Logging" and Sampling Oil and Gas Wells While Drilling*, Instruments, June 1940, pp. 155–166.

All this information is assembled in the form of a mud analysis log which consists of curves showing rate-of-penetration, oil content, and gas content recorded at their correct depths.[2]

All the equipment used in the process is housed in trucks or trailers to render it thoroughly portable.

Mud analysis logging is used both for the economic completion of wells in known producing areas and for complete logging of exploratory wells. Mud analysis logging in known producing areas has a two-fold use. The first application consists of logging a known producing zone to eliminate coring and to indicate that portion of the horizon which may be most advantageously produced. Gas caps may be located in order that they may be cased off. The log will show those portions of the producing horizon which should be acidized or shot. In problems involving selective completion, the log will indicate the zones which may best be opened to the well bore.[3,4,5]

Mud analysis logs of routine completions usually cover a limited portion of the hole and involve only a few hours of drilling. Fig 1 illustrates a log derived from the completion of a well in a single zone. The log shown is that of a Southwest Arkansas well located in the Midway Oil Field of Lafayette County. The producing zone is a Jurassic oolitic limestone. The solid curve appearing on the left-hand side of the log represents the rate of penetration of the bit. The slow drilling part of the curve is near the center of the log and the rapid drilling section "breaks" toward the left in proportion to the increase in rate-of-penetration. This curve indicates the porous and permeable sections of the well. The solid curve on the right-hand side of the log represents the crude oil content of the drilling mud passing the bit as the section was drilled which, in turn, represents the oil saturation of the zone. The broken or dotted curve appearing with the oil curve is the gas curve and bears the same relation to the formation penetrated, with respect to gas, as does the oil curve in respect to oil. The oil and

[2] The mud analysis logging process is covered by the following U. S. Patents: 1,720,325, 2,166,212, 2,213,138, 2,124,674, 2,229,884, and 2,342,273.

[3] J. T. Hayward, *Continuous Logging at Rotary-Drilling Wells*, Paper before the Division of Production, American Petroleum Institute, annual meeting, November 11–15, 1940.

[4] Elton Sterrett, *Analysis of Mud Returns Locates Oil and Gas Zones*, The Oil Weekly, March 31, 1941, pp. 49–58.

[5] Harry F. Simons, *Applying Formation Logging through Mud Analysis*, Oil and Gas Journal, October 2, 1941, pp. 33–37.

gas curves are plotted in semiquantitative logging units based on arbitrary standards developed by experience. The log appearing in Fig. 1 indicates a thick and porous producing zone with excellent oil and

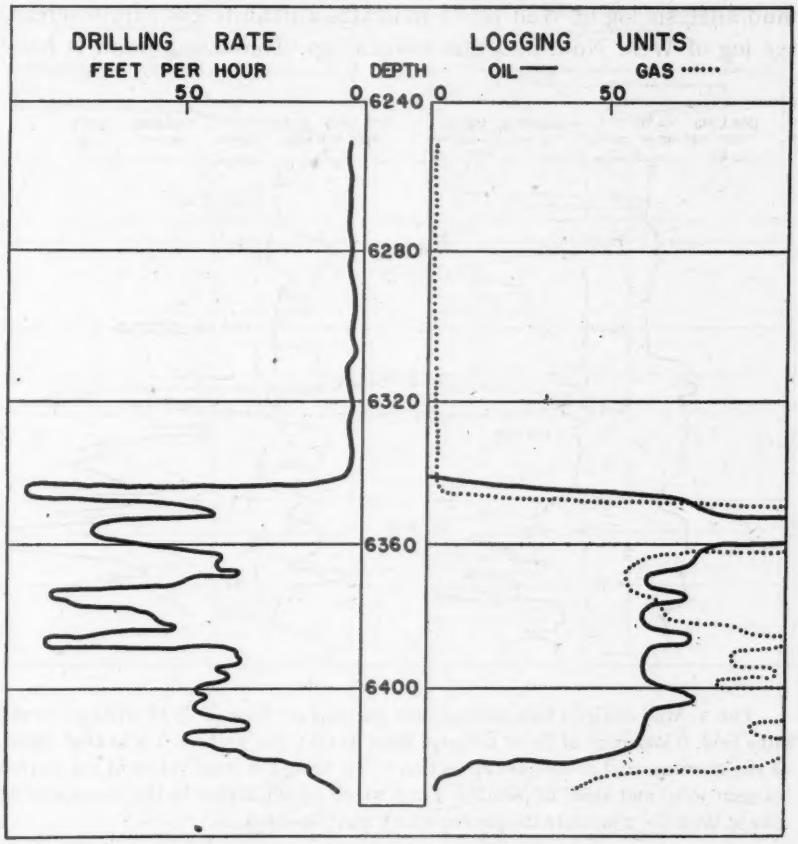

FIG. 1. Typical mud analysis log obtained during the drilling of a producing zone. The porous zone is indicated on the drilling rate curve by an increase in the plotted values between 6345′ and 6430′. Excellent oil and gas content of this zone are indicated by the large increases in both the oil and the gas curves. No gas cap is indicated. (Midway field of Lafayette County, Arkansas.)

gas content. In this case, the casing was run to the top of the zone and the well completed with a good flow of oil and gas.

Gas caps are frequently difficult to locate by coring, and mud analysis logging offers an excellent and economical means of identifying

the gas producing zone in order that it may be cased off. The two wells in Fig. 2 are in the Goldsmith Field of Ector County, West Texas. Both wells are producing from the same zone in Permian porous dolomite, but well No. 1 is located in the gas cap section of the field. The mud analysis log of Well No. 1 indicates a definite gas cap, whereas, the log of Well. No 2 indicates no gas cap. The casing point is indi-

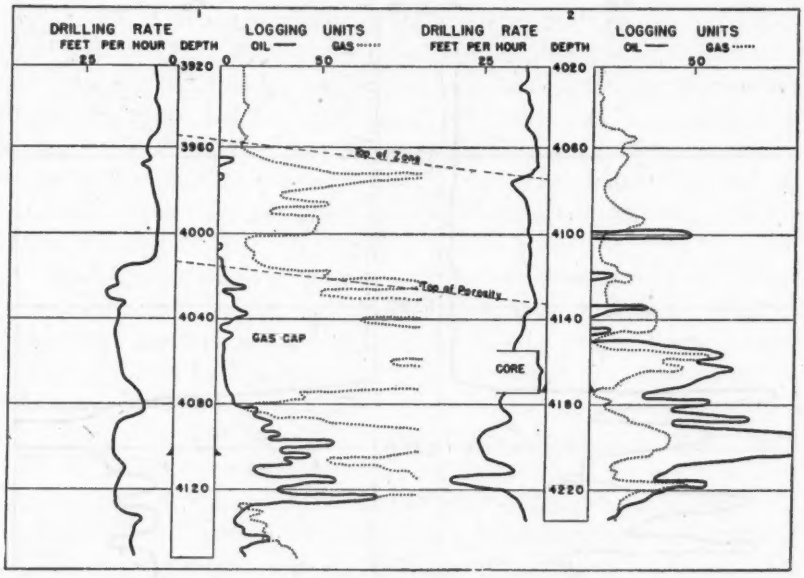

FIG. 2. Mud analysis logs showing how gas caps are located. Both wells are in the same field. (Goldsmith of Ector County, West Texas), but well No. 1 is located higher on the structure and in the gas cap section of the field. The large values of gas plotted between 3965′ and 4080′ in Well No. 1 and which do not appear in the corresponding zone in Well No. 2 indicate the gas cap which must be cased off.

cated on the two logs. Well No. 1 was completed for 473 barrels per day with an initial gas-oil ratio of 1480. Well No. 2 was completed for 1034 barrels per day with an initial gas-oil ratio of 1076.

The second application in known producing areas involves logging zones up the hole which are to be opened for testing and producing at a later time. In many fields most completions are made in one well-defined producing horizon. Frequently, however, the drill passes through zones which later may be opened to prolong the life of the well after the outstanding zone has been depleted. The upper zones

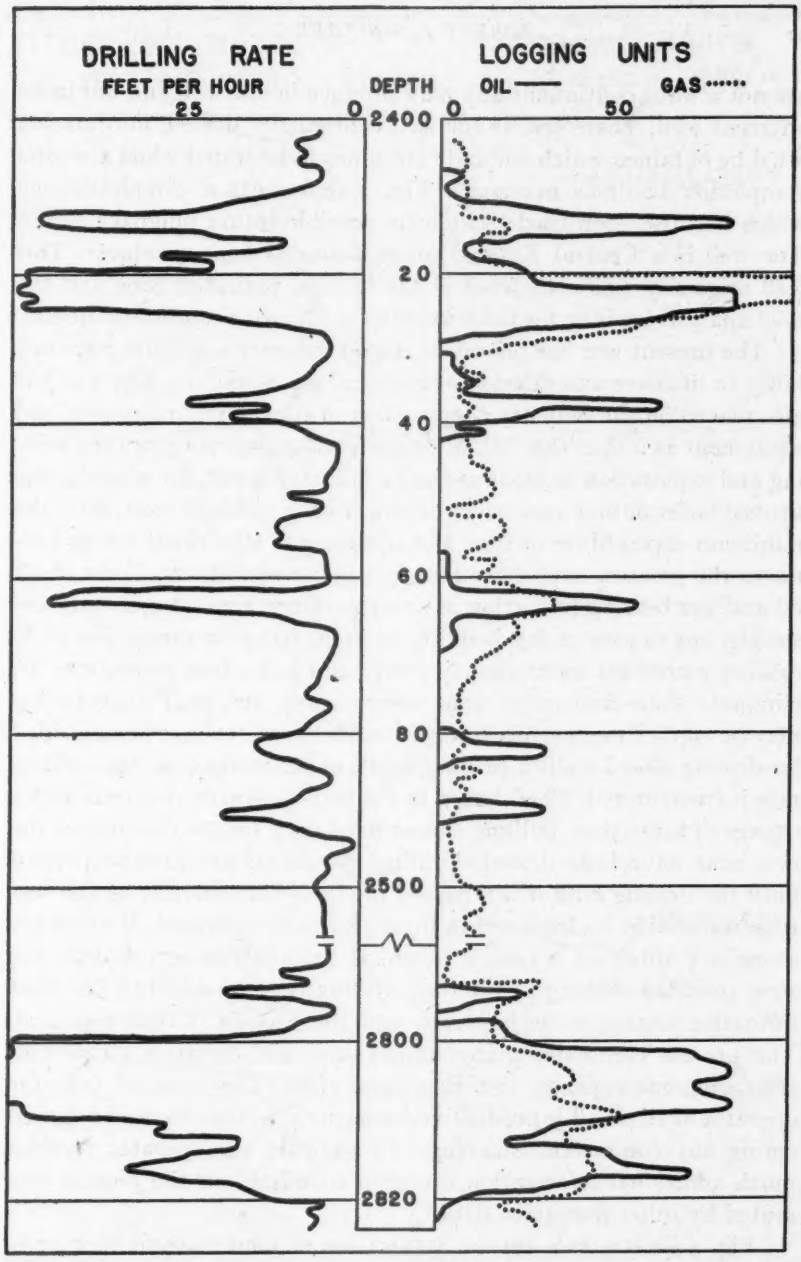

FIG. 3. Mud analysis log of a well (Central Kansas Lower Pennsylvanian producer) containing several possible producing zones above a lower zone (2800′–2820′) in which the well has been originally completed. The log will serve as a guide to later testing when the lower zone has been depleted.

are not always continuous and may produce in one well and not in an adjacent well, Therefore, as the well is originally drilled, information must be obtained which will indicate zones to be tested when a second completion becomes necessary. Fig. 3 represents a completion log which has also been used to indicate possible future plugback zones. The well is a Central Kansas Lower Pennsylvanian producer. This well originally was completed in the bottom indicated zone and the mud analysis log is on file to be used in the future as conditions dictate.

The present war has placed on the oil industry a definite responsibility to discover and develop new oil and gas resources. The war has also placed on the industry the problem of conserving manpower and equipment as it does this job. Mud analysis logging has given the drilling and exploration sections of the oil industry a method whereby the utmost information can be obtained from a wildcat well with the minimum expenditure of time and equipment. Minimized coring produces the greatest saving realized in wildcat operations. Cores of all oil and gas bearing formation in an exploratory well may be very desirable, but to core each possibility or each change in formation while drilling represents an extremely costly and hazardous procedure. To eliminate shale and other unnecessary cores, the mud analysis log may be applied to good advantage. Excellent results have been yielded by drilling ahead until a drilling break or an increase in the drilling rate is encountered. This change in the rate-of-penetration indicates a change of formation. Drilling is continued until two to four feet of the new zone have been drilled. Drilling operations are then suspended until the drilling mud which passed the bit while penetrating the section in question is circulated to the surface and analyzed. If oil or gas shows are obtained, a core is taken. If the analysis reveals that the zone contains nothing of interest, drilling is resumed until the next formation change is encountered and the process is then repeated. The process eliminates many unnecessary and negative cores with their inherent expense, lost time, and risks. This method tells the operator of all possible productive formations, so that he need not miss coring any commercial showings. In addition, the operator receives much additional information useful in rounding out the picture presented by other formation data.[6]

Fig. 4 illustrates a typical application of mud analysis logging to control coring. The section of log shown represents a sand and shale series of the Texas Gulf Coast Oligocene. The first two sections shown

[6] R. W. Wilson, *Application of Mud Analysis Logging in Gulf Coast Area*, The Oil and Gas Journal, June 25, 1942, pp. 86–87.

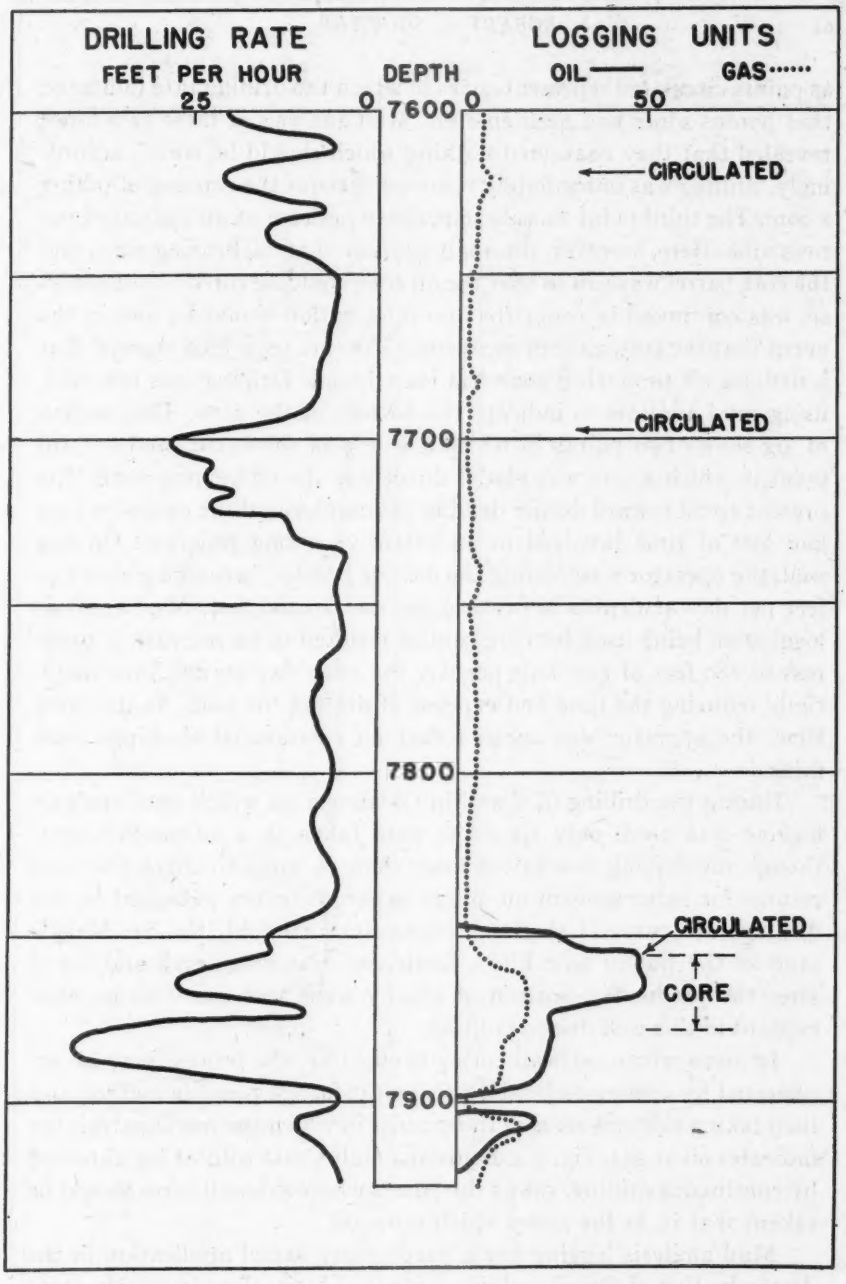

FIG. 4. Section of a log showing the procedure in drilling a wildcat well using mud analysis logging to minimize coring. Porous zones are indicated at 7,620 feet and 7,690 feet. The log revealed that these zones did not contain oil or gas and that it was not desirable to core them. The log revealed that the porous zone at 7,845 feet did contain oil and gas, thus making it possible to place a core directly in the zone. The section of log shown is in a sand and shale series in Gulf Coast Oligocene.

as points circulated represent zones in which the drilling rate indicated that porous zones had been entered. Mud analysis of these two zones revealed that they contained nothing which should be cored; accordingly, drilling was immediately resumed without the expense of taking a core. The third point was also circulated because of an indicated porous zone. Here, however, the analysis showed an oil bearing zone, and the core barrel was run so that the oil zone could be cored. Mud analysis was continued in order that no information would be lost in the event that the core was not recovered. The core recovered showed that a definite oil producing zone has been found. Drilling was resumed, using mud analysis to indicate the bottom of the zone. This section of log shows two points in which a core was eliminated and a third point in which a core was placed directly in the oil bearing zone. The present trend toward deeper drilling has emphasized the excessive cost and loss of time involved in an extensive coring program. On one well, the operator was "coring the drilling breaks," averaging about 50 feet per day at depths between 9,000 and 10,000 feet. Mud analysis logging on being used for core control resulted in an increase in progress to 180 feet of new hole per day for a ten-day period, thus materially reducing the time and expense of drilling the hole. At the same time, the operator was assured that no commercial showings were missed.

During the drilling of a well in Oklahoma on which mud analysis logging was used, only six cores were taken in a 10,000-foot test, though the drilling was halted more than 50 times to check the mud returns for indications of oil or gas in porous bodies indicated on the drilling rate curve. Using this exploratory method, the St. Mary's sand in the Bayou Sale Field, Louisiana, was discovered and cored after the productive horizon of nearby wells was found to be nonexistent in this well due to faulting.

In areas where sidewall coring is effective, the process may be accelerated by drilling to total depth by the fastest possible method and then taking sidewall cores in those zones in which the mud analysis log indicates oil or gas. Fig. 5, a Louisiana Gulf Coast wildcat log obtained by continuous drilling, shows the points where sidewall cores should be taken; that is, in the zones which show oil.

Mud analysis logging has a particularly useful application in the determination of the oil and gas content of formations in certain areas where interpretation of electrical logs is difficult or impossible. Two such areas are the Permian Basin of West Texas and the Eocene Wilcox of the Gulf Coast. The high salt content of the muds used in drill-

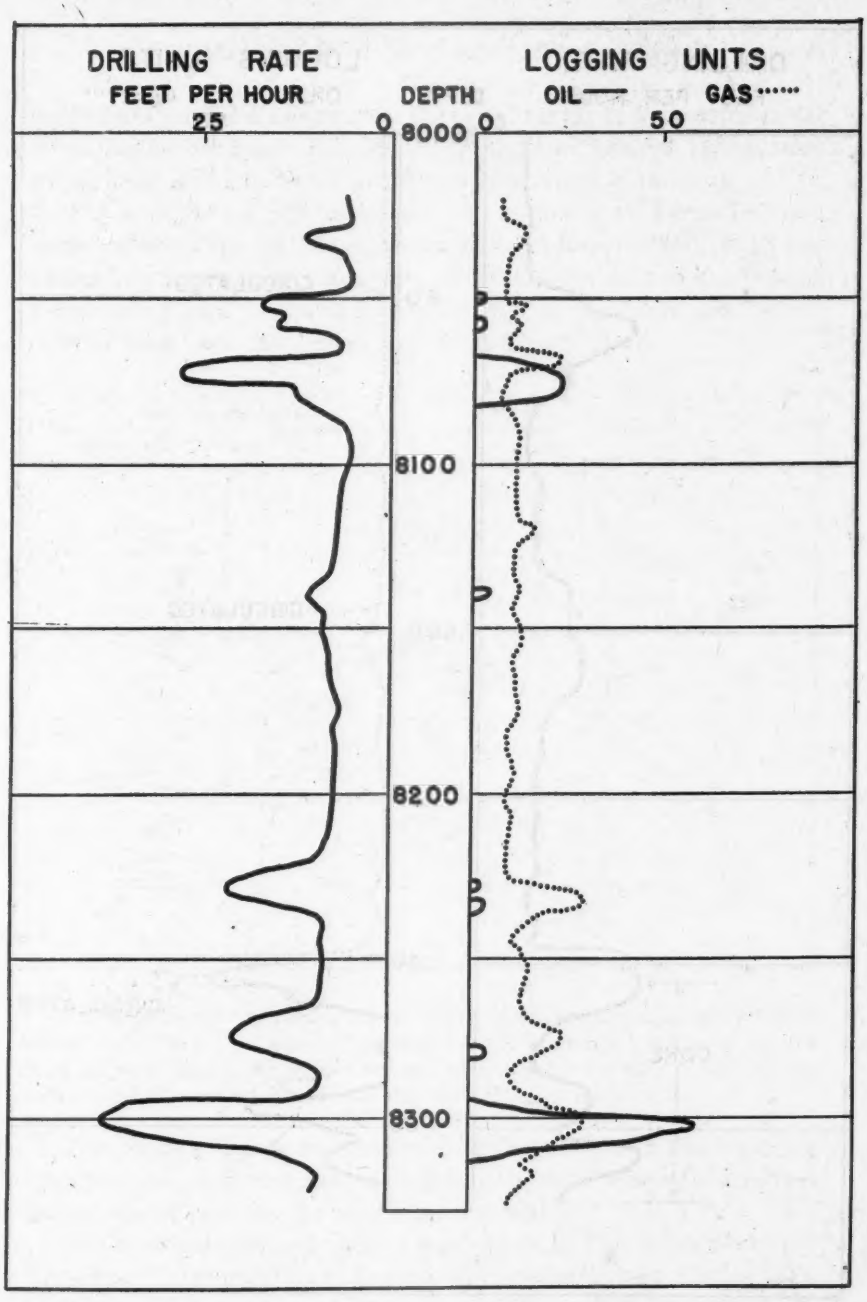

FIG. 5. Section of a mud analysis log taken from a Louisiana Gulf Coast wildcat well which was drilled to total depth without coring or testing in any manner. The log was then used to pick sidewall coring points at 8070′, 8230′, 8275′, and 8300′.

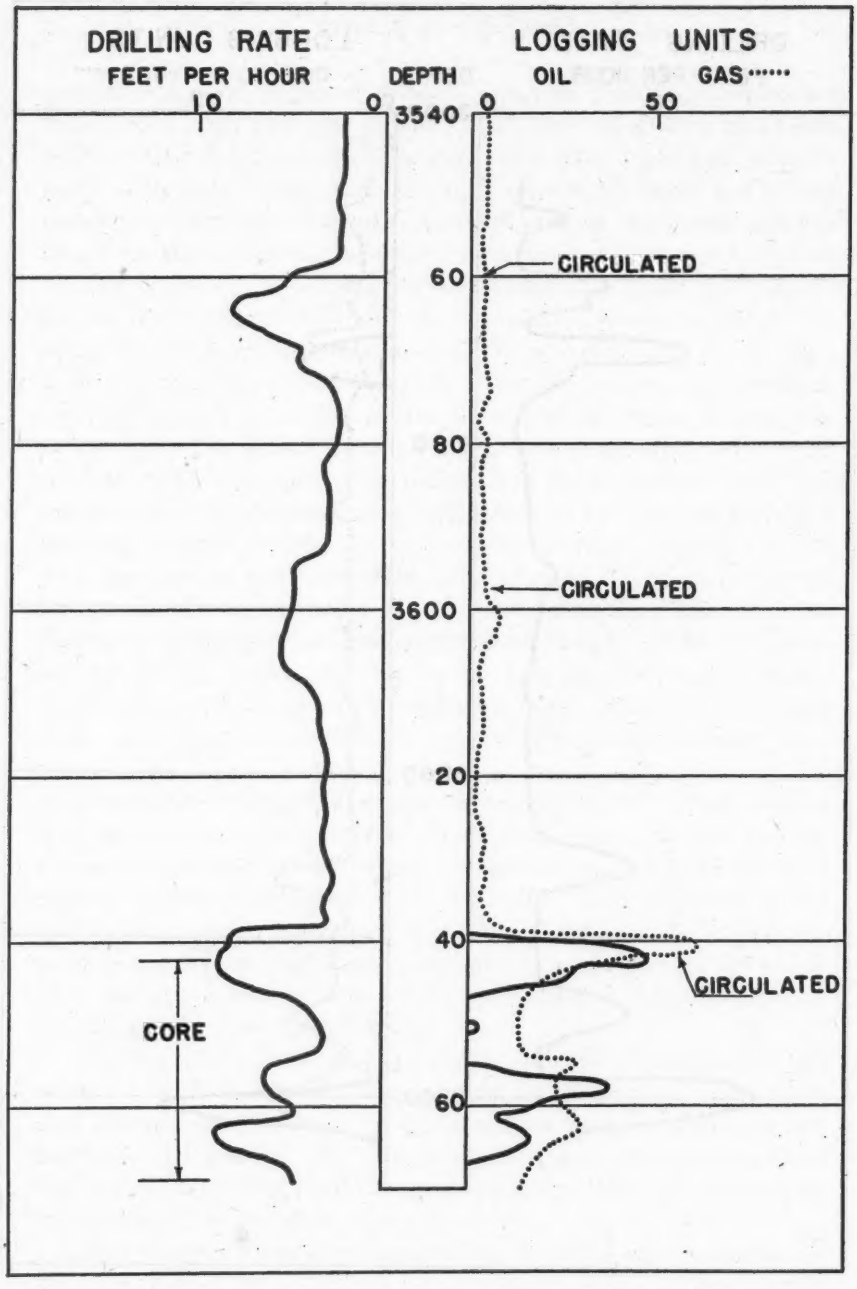

FIG. 6. Mud analysis log of a West Texas discovery well drilled by the controlled coring procedure. Unnecessary cores were eliminated at 3560′ and 3596′. The zone at 3638′ was located by the log and cored.

ing in the Permian Basin renders the electrical log of little value in determining fluid content. For this reason, the mud analysis log has been widely used in wildcat and completion operations in this area.

Fig. 6 is the log of a discovery well in the West Texas Permian Basin drilled by the mud analysis controlled coring method. With this method no unnecessary cores were taken, but the oil and gas bearing zones were cored. The well was completed in the lower zone and a possible plug back completion is indicated up the hole.

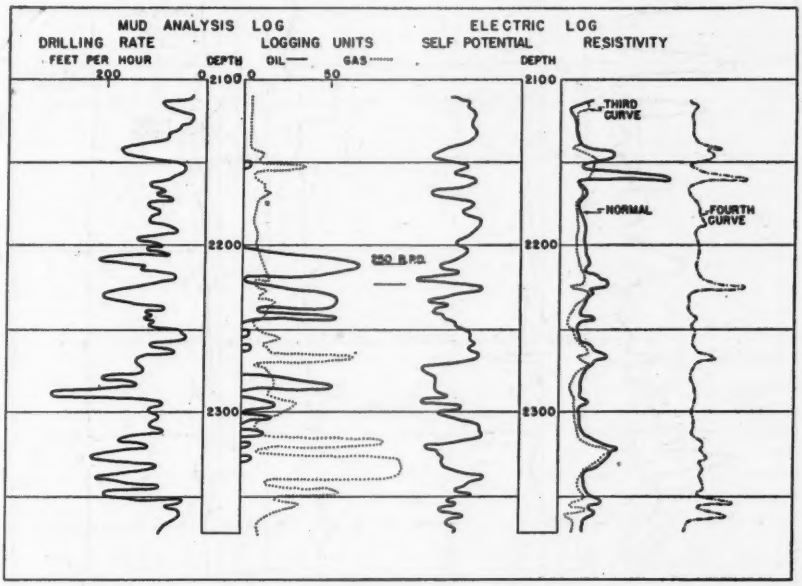

FIG. 7. Composite mud analysis log and electrical log of a Central Louisiana Eocene Wilcox well (Placid Oil Company Louisiana Central Lumber Company no. 22, Olla Field, La Salle Parish) showing how the mud analysis log can be used to interpret the fluid content of the many sands in this difficult-to-interpret zone.

The Eocene Wilcox presents a difficult problem in electrical log interpretation, and mud analysis logs have given much useful information on the oil and gas content of these zones.

The mud analysis and electric logs shown in Fig. 7 illustrate the difficulty of interpretation of Eocene Wilcox electric logs. The log used for the illustration is that of the Placid Oil Company's Louisiana Central Lumber Company No. 22 well located in the Olla Field, La Salle Parish, Central Louisiana. The self potential curve of the electric log indicates the porous zones, but the resistivity curves do not define the

oil and gas content of the zones as clearly as do the oil and gas curves of the mud analysis log. The well shown is a completion in a known producing area. The mud analysis log furnished information on the best zone to test which led to the completion of a 250-barrel well at the point marked on the log. Fig. 8 shows the electric and mud analysis

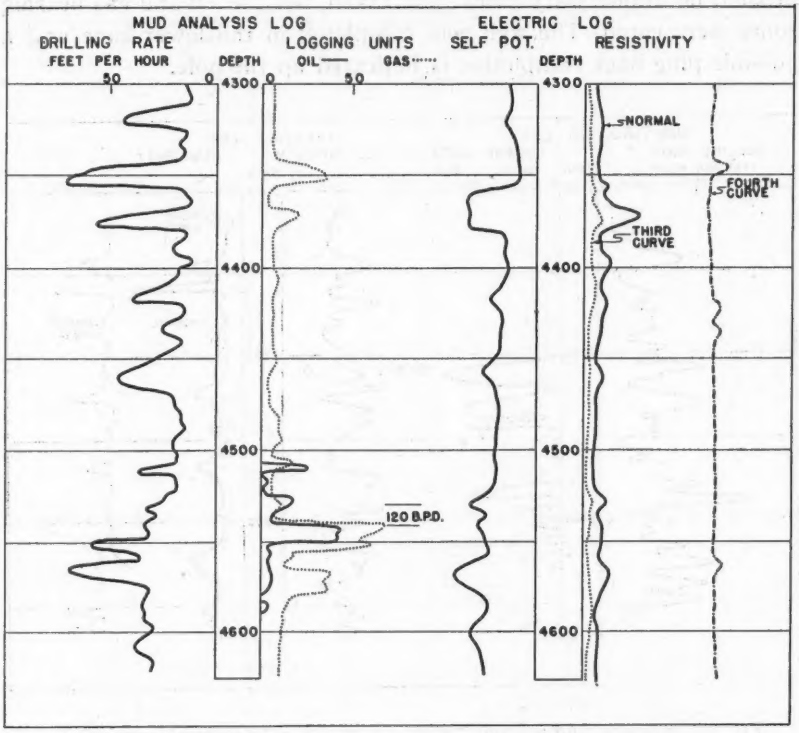

FIG. 8. A comparison between the mud analysis log and the electrical log of a Central Louisiana Eocene Wilcox well drilled without coring. A new producing zone was opened when the zone from 4529′ to 4540′ was tested as the result of the shows on the mud analysis log.

logs of an Eocene Wilcox field opener in Central Louisiana drilled without coring. The show on the mud analysis log caused the operator to sidewall core and drill stem test, thereby proving the zone as a producer.

Interpretation of the gas content of cores from gas wells and differentiation between oil and gas on the electric log presents many difficulties. The mud analysis log offers a direct method of identifying zones bearing gas. Fig. 9 illustrates a completion log in the Pennsyl-

vanian zone of the Chickasha Natural Gas Field of Grady County, Oklahoma. The drilling rate curve defines the porous zones and the gas curve clearly shows the main gas bearing body. The electric log

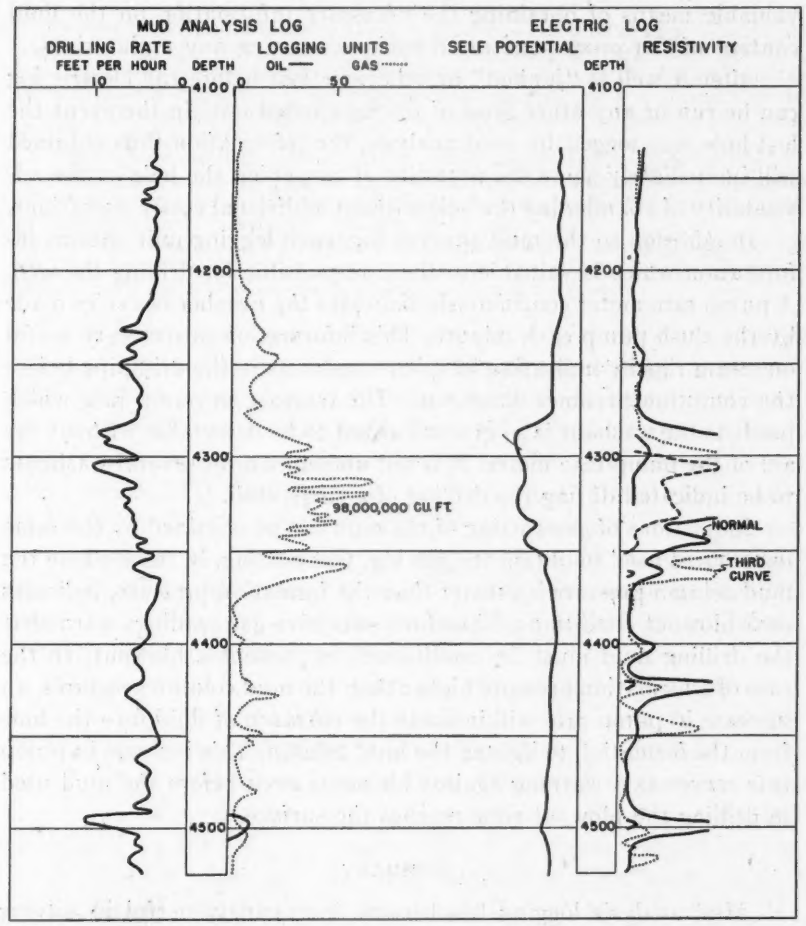

FIG. 9. A composite mud analysis and electric log of a well in the Chickasha gas field of Grady County, Oklahoma. The gas curve defines the gas producing body by directly indicating gas as distinguished from oil.

shows the porous zones and shows them to contain either oil or gas or both, but it does not differentiate between oil and gas. This particular well was completed by running casing to bottom and perforating in the main gas body. The well came in for ninety-eight million cubic feet of dry gas per day.

Occasionally, while drilling wells, unusual conditions develop, such as abnormally high gas pressures or dangerously sloughing shales, which render any interruption of the drilling processes extremely hazardous. Under these conditions, the mud analysis log has proved a valuable means of obtaining the necessary information on the fluid content of the zones penetrated without running any undue risks.

Often a well is "junked" or otherwise lost before the electric log can be run or any other form of testing carried out. In the event the lost hole was logged by mud analysis, the information thus obtained will immediately show the necessity of reopening the hole or the advisability of abandoning the hole without additional costly operations.

In addition to the mud analysis log, each logging unit obtains information which is valuable to those responsible for drilling the well. A pump rate meter continuously indicates the number of cycles made by the slush pump each minute. This information proves very useful on steam rigs by indicating incipient washouts in the drill pipe before the condition becomes dangerous. The increase in pump rate which predicts the washout is so gradual as not to be detectable without the aid of the pump rate meter. It is not uncommon for several washouts to be indicated during the drilling of a single well.

Indications of gas-cutting of the mud can be obtained by the same instrument used to obtain the gas log. Gas-cutting, in cases where the mud column pressure is greater than the formation pressure, indicates near-blowout conditions. Therefore, excessive gas readings warn that the drilling mud must be conditioned to prevent a blowout. In the case of a formation pressure higher than the mud column pressures, an increase in pump rate will indicate the entrance of fluid into the hole from the formation to lighten the mud column. This increase in pump rate serves as a warning against blowouts even before the mud used in drilling the blowout zone reaches the surface.

SUMMARY

Mud analysis logging has become increasingly useful in solving many of the difficult problems encountered in routine and exploratory drilling. In well completion operations this system of logging has provided much additional information in cases where the electric log and cores are not effective or are too costly. In the field of exploratory drilling mud analysis logging has made it possible to drill wildcat wells more rapidly at reduced expense and yielding more formation information than in the past.

MOTION OF A RIGID SPHERE IN AN ACOUSTIC WAVE FIELD*

ALFRED WOLF†

ABSTRACT

A rigid sphere in the field of plane acoustic waves in a fluid or in an elastic solid medium is subjected to harmonic forces in the direction of propagation of the waves, and proportional to their amplitude. The response curve is a function of the ratio of the circumference of the sphere to the wave length, and of the ratio of the mass of the sphere to the mass of the displaced medium. In an elastic solid, Poisson's ratio must also be included among the variables.

The response curve in fluids decreases continuously with decreasing wave length. In elastic solid media, the response curve has a maximum which is due to resonance effects. In general, the greater the mass of the sphere the smaller the response except in the neighborhood of resonance in elastic solid media.

The scattering of acoustic waves by a rigid sphere is determined. The potential of scattered waves is developed in a series of spherical harmonics; it is shown that only the first order coefficients are affected by the motion of the sphere.

The interpretation of instrumental records of wave motion in fluids or in solids requires a consideration of the mechanical interaction of the recording apparatus and the medium. In general, the insertion of any device modifies the motion in its immediate neighborhood, and results in a decrease in amplitude at high frequencies; the decrease begins at the point at which the wave length is of the same order as the linear dimensions of the detector. A quantitative analysis can be carried out if it is postulated that the detector of wave motion, e.g., a geophone, is enclosed in a rigid container of simple geometrical form. For the case of a sphere, the problem is soluble in finite form without much analytical complication.

The present paper deals with the motion of an infinitely rigid sphere in acoustic wave fields in fluids and in solids. The scattering of such waves by a rigid sphere is another problem considered. In Section 1, which serves as an introduction, the problem is discussed from a general point of view, and, for convenience, the final formulae are stated. In Section 2, the properties of those special solutions of the wave equation which are employed subsequently are briefly considered. Section 3 deals in some detail with the problem of motion in a fluid and with the scattering of acoustic waves by the moving sphere. In Section 4, the case of an infinitely rigid sphere in an elastic solid medium is treated; the amplitude of motion of the sphere and the scattering are derived from the general equations of the theory of elasticity.

* Manuscript received May 12, 1944.

† Geophysical Research Corporation, Tulsa, Oklahoma.

1. INTRODUCTION

The analytical problem may be formulated as follows: A rigid sphere of given mass is placed in an acoustic medium, fluid or solid, in which longitudinal waves are propagated. It is required to find the amplitude of motion of the sphere as a function of wave length. The assumption is made that the rigidity of the sphere is very great compared to the elastic moduli of the medium; the theory is developed for an infinitely rigid sphere. Effects of viscosity and other irreversible losses are neglected. The method employed is a direct application of wave potential theory. The potential of the incident plane waves is expanded in series of spherical surface harmonics, and a scattered wave potential is superposed to satisfy the proper boundary conditions. In fluids, the component of velocity normal to the surface of the sphere at any point on the boundary must be the same as the normal component of the velocity of the sphere at that point. In solid media, it is required that the displacement at the boundary of the sphere, both normal and tangential, follow faithfully the motion of the sphere; the latter is considered to be firmly attached to the medium at all points of its boundary. The force acting on the sphere depends only on the first order term in the development of stress in a series of spherical harmonics. For this reason closed algebraic formulae are obtained for the amplitude of motion of the sphere. The development of the theory requires that the transformation of longitudinal into scattered transverse waves in solid elastic media be considered; this effect is absent in fluids.

In fluids, the force acting on the sphere at low frequencies is given by the product of one-half the mass of the fluid displaced by the sphere and of relative acceleration.[1] Since the force of inertia is proportional to the mass of the sphere and to absolute acceleration in space, the response is qualitatively inversely proportional to the mass of the sphere when the absolute motion is small. By response is meant the ratio of the amplitude of the absolute motion of the sphere to the amplitude of wave motion in the medium. For sufficiently high frequencies, when the wave length is of the same order as the circumference of the sphere, the force acting on the sphere increases only slowly with frequency and the response begins to decrease.

In solid elastic media, it is relative displacement which determines the force on the sphere at low frequencies. Because of this fact

[1] Cf. Lamb: *Hydrodynamics*, 5th ed., Art. 92.

the sphere follows exactly the motion of the medium no matter what its mass, provided only that the frequency is sufficiently low. Elastic forces proportional to relative displacement and the inertia of the sphere cause the appearance of resonance in this case; the damping of the motion is due to scattering of elastic waves by the sphere.

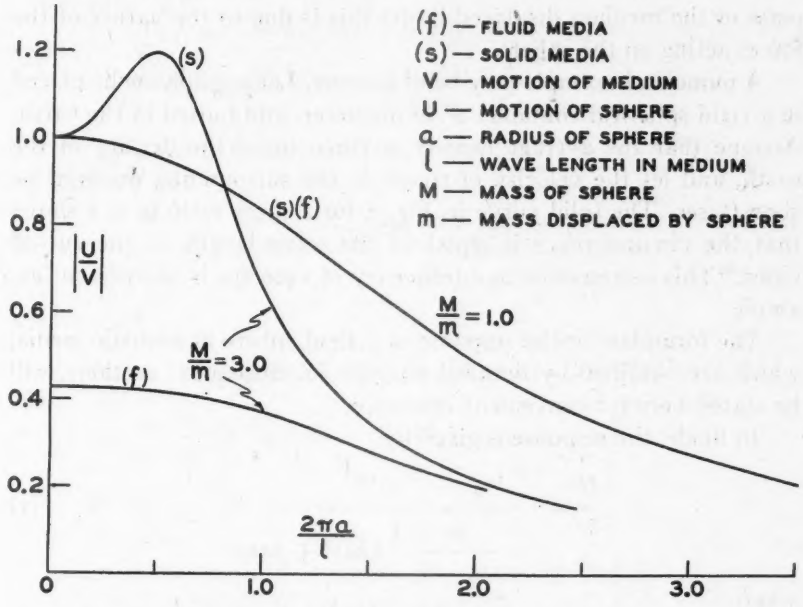

FIG. 1. Response curves of an infinitely rigid sphere in acoustic wave fields in fluids and in elastic solid media.

The response of the sphere both in fluid and in solid media can be expressed as a function of two variables, namely the ratio of the circumference* of the sphere to the wave length of incident radiation and the ratio of the mass of the sphere to the mass of the medium displaced by it. A few response curves are shown in Fig. 1. The abscissa is the ratio of circumference to wave length. The curves are drawn for two values of the mass ratio, namely 1:1 and 3:1. It is assumed that Poisson's ratio of the elastic solid has the value 0.25. In the special case when the mass ratio is 1:1 the response is identical for solids

* The ratio of circumference to wave length is used in preference to the more usual ratio of diameter to wave length because it appears in this form in all equations.

and for fluids. In Fig. 1, this response function is shown by the $(s)(f)$ curve $M/m=1.0$. When the mass ratio $M/m=3.0$, the response of the sphere in solids—(s) curve in Fig. 1—shows a pronounced resonance. The response in a fluid for the mass ratio 3:1—(f) curve in Fig. 1—is much smaller. In general, the response in fluids is smaller than in solids when the mass of the sphere is much greater than the mass of the medium displaced by it; this is due to the nature of the forces acting on the sphere.

A numerical example may be of interest. Let a geophone be placed in a rigid spherical container 8″ in diameter, and buried in the earth. Assume that the average density is three times the density of the earth, and let the velocity of sound in the surrounding material be 5000 ft/sec. The solid curve in Fig. 1 for a mass ratio of 3:1 shows that the circumference is equal to the wave length at the cut-off point.* This corresponds to a frequency of 2400 cps in the present example.

The formulae for the response of a rigid sphere in acoustic media, which are obtained by detailed analysis in subsequent sections, will be stated here for convenient reference.

In fluids, the response is given by

$$\frac{U}{V}=\frac{e^{jha}}{\sigma-\frac{3\sigma-1}{6}(ha)^2+j\sigma ha} \tag{1}$$

where

$j=\sqrt{-1}$

U is velocity of sphere

V is particle velocity in fluid

$$\sigma=\frac{1}{3}\left(1+2\,\frac{M}{m}\right)$$

M is mass of sphere

m is mass of fluid displaced by sphere

$h=2\pi/l$

l is wave length

a is radius of sphere

* This is taken as the point at which the response falls to 0.707 of the value it reaches for long wave length.

Since phase is involved in Eq. 1, the phase of fluid motion at some time and position must be specified. The choice is made in such manner that the phase of the undisturbed wave motion is *zero* at the center of the sphere at the time $t=0$.

The absolute value of U/V which is plotted in Fig. 1 is obtained from

$$\left|\frac{U}{V}\right| = \frac{1}{\sqrt{\sigma^2 + \frac{\sigma}{3}(ha)^2 + \frac{(3\sigma-1)^2}{36}(ha)^4}}. \tag{2}$$

In solids, the response equation is much more involved. It may be written as

$$\frac{U}{V} = \frac{(1 - \frac{1}{3}(ka)^2 + jka)e^{jha}}{D} \tag{3}$$

with

$$D = 1 - (hk + \tfrac{1}{9}k^2 + \tfrac{2}{9}h^2)a^2 + j[h + k - hka^2(\tfrac{1}{9}k + \tfrac{2}{9}h)]a$$
$$- \frac{M}{9m}[h^2 + 2k^2 - h^2k^2a^2 + jhka(h + 2k)]a^2$$

$h = 2\pi/l$
$k = 2\pi/l_1$
l = wave length of longitudinal waves
l_1 = wave length of transverse waves

When Poisson's ratio for the elastic solid medium has the value 0.25, $k^2 = 3h^2$, and Eq. 3 may be written as

$$\frac{U}{V} = \frac{(1 - h^2a^2 + 1.732jha)e^{jha}}{D_1} \tag{4}$$

with

$$D_1 = 1 - 2.288h^2a^2 + jha(2.732 - 0.718h^2a^2)$$
$$- \frac{M}{m}h^2a^2(0.777 - 0.333h^2a^2 + 0.859jha).$$

For the special case $M/m = 1$, Eq. 3 can be simplified considerably because the numerator on the right hand side of Eq. 3 is a factor of D. It follows that

$$U/V = e^{jha}/(1 + jha - \tfrac{1}{3}h^2a^2) \quad \text{for} \quad M = m$$

which is identical with the fluid formula for $M/m = 1$.

In order that Eqs. 1–4 be valid, the rigidity of the sphere must be much greater than the elastic moduli of the medium. In practical problems this condition is more apt to be satisfied in fluids than in solids.

2. SOLUTIONS OF THE WAVE EQUATION

The partial differential equation of propagation of harmonic waves

$$\nabla^2\phi + h^2\phi = 0 \tag{5}$$

has solutions proportional to spherical surface harmonics. In spherical polar coordinates they can be expressed as

$$f_n(hR) \cdot P_n(s) \tag{6}$$

where

$R^2 = x^2 + y^2 + z^2$

$s = z/R$

P_n Legendre polynomial of order n

$$\begin{aligned} f_n(\xi) &= \xi^n \left(\frac{1}{\xi}\frac{d}{d\xi}\right)^n \frac{e^{-j\xi}}{\xi} \\ &= (-1)^{n+1} j \sqrt{\frac{\pi}{2\xi}}\, H^{(2)}_{n+1/2}(\xi) \end{aligned} \tag{7}$$

in which $H^{(2)}{}_{n+1/2}$ are Hankel's functions.[2] The properties of f_n stated below may be derived directly from its definition or by reference to the properties of Hankel functions.

$$\left(\frac{d^2}{d\xi^2} + \frac{2}{\xi}\frac{d}{d\xi} + 1 - \frac{n(n+1)}{\xi^2}\right) f_n = 0 \tag{8a}$$

$$f_n' - \frac{n}{\xi} f_n = f_{n+1} \tag{8b}$$

$$f_n' + \frac{n+1}{\xi} f_n = -f_{n-1} \tag{8c}$$

$$f_{n+1} = -f_{n-1} - (2n+1)\frac{f_n}{\xi} \tag{8d}$$

[2] Cf. Jahnke-Emde: *Tables of Functions*, 2nd ed., p. 199–204.

The f_n's are related to Bessel functions of half odd integral order through

$$J_{n+1/2}(\xi) = (-1)^n \sqrt{\frac{2\xi}{\pi}} \frac{f_n^*(\xi) - f_n(\xi)}{2j}$$

where f_n^* is the conjugate complex of f_n. From the well known expansion*

$$e^{-jhRs} = \sum_{n=0}^{\infty} (2n+1)(-j)^n \sqrt{\frac{\pi}{2hR}} J_{n+1/2}(hR) P_n(s)$$

it follows that

$$e^{-jhz} = e^{-jhRs} = \sum_{n=0}^{\infty} (2n+1) j^n \frac{f_n^*(hR) - f_n(hR)}{2j} P_n(s) \quad (9)$$

a relation which can be easily verified directly by a recourse to Eq. 8d and 10e, 10g, 11a, 11b given below.

The following properties of Legendre polynomials which will be used are listed for reference.[3]

$$\frac{d}{ds}\left\{(1-s^2)\frac{dP_n}{ds}\right\} + n(n+1)P_n = 0 \quad (10a)$$

$$P_{n+1}' - sP_n' = (n+1)P_n \quad (10b)$$

$$(2n+1)sP_n = (n+1)P_{n+1} + nP_{n-1} \quad (10c)$$

$$sP_n' - P_{n-1}' = nP_n \quad (10d)$$

$$P_{n+1}' - P_{n-1}' = (2n+1)P_n \quad (10e)$$

$$(s^2-1)P_n' = nsP_n - nP_{n-1} \quad (10f)$$

$$\int_{-1}^{1} P_n^2 \cdot ds = \frac{2}{2n+1}, \qquad \int_{-1}^{1} P_n P_m ds = 0 \quad \text{for} \quad n \neq m. \quad (10g)$$

Finally, explicitly,

$$f_0(\xi) = \frac{1}{\xi} e^{-j\xi}, \qquad f_1(\xi) = -\left(\frac{j}{\xi} + \frac{1}{\xi^2}\right) e^{-j\xi} \quad (11a)$$

$$f_2(\xi) = \left(-\frac{1}{\xi} + \frac{3j}{\xi^2} + \frac{3}{\xi^3}\right) e^{-j\xi}$$

$$P_0 = 1, \qquad P_1 = s, \qquad P_2 = \tfrac{3}{2}s^2 - \tfrac{1}{2}. \quad (11b)$$

* Cf. Lamb, *Hydronamics*, 5th ed., Art. 296, p. 486.

[3] Whittaker and Watson: *Modern Analysis*, 3rd ed., Chapt. 15.

3. MOTION OF AN INFINITELY RIGID SPHERE IN FLUIDS

Let an infinitely rigid sphere of radius a and mass M be placed in a fluid medium in which acoustic waves are propagated. A rectangular coordinate system with its origin at the center of the sphere is chosen in such manner that the $+z$ axis is in the direction of propagation of the waves. The particle velocity in the fluid at a great distance from the sphere is then given by

$$V \cdot e^{-jzh} \tag{12}$$

where

$h = 2\pi/l$

l wave length

The time factor

$$e^{j\omega t}$$

is omitted in Eq. 12 as well as in all subsequent equations. It is desired to determine the motion of the sphere and the scattering of waves in the fluid. The procedure follows closely the work of Lord Rayleigh[4] who determined the scattering produced by a stationary sphere. It will be shown that only first order scattering potentials are affected by the motion of the sphere.

The particle velocity at any point in the fluid is given by

$$-\nabla(\phi + \psi). \tag{13}$$

$\phi+\psi$ is the total velocity potential, ϕ being the velocity potential of the plane waves of Eq. 12, and ψ the velocity potential of scattered waves which is to be determined.

The velocity potentials satisfy Eq. 5; the pressure in the fluid is given by

$$\delta p = \rho \frac{\partial(\phi + \psi)}{\partial t} \tag{14}$$

in which ρ is the density of the fluid. The velocity potential of the plane waves of Eq. 12 is

$$\phi = \frac{V}{jh} e^{-jhz} = \sum \phi_n P_n(s), \tag{15}$$

[4] Rayleigh: *Theory of Sound*, 2nd ed., vol. II, Chapt. 17.

and according to Eq. 9

$$\phi_n = V(2n+1)j^n \frac{f_n(hR) - f_n^*(hR)}{2h}. \tag{16}$$

The scattering potential ψ may be expanded as

$$\psi = \sum A_n f_n(hR) P_n(s). \tag{17}$$

The coefficients A_n are to be determined from boundary conditions at the surface of the sphere and from the dynamic equation of motion. The A_n's give directly the intensity of scattering of the various orders.

Let the velocity of the sphere in the direction $+z$ be denoted U. The component of velocity of the fluid normal to the surface of the sphere must then be given by

$$U\frac{z}{R} = UP_1(s) \quad \text{for} \quad R = a.$$

Hence the boundary conditions require

$$-\left(\frac{d\phi}{dR} + \frac{d\psi}{dR}\right)_{R=a} = UP_1(s). \tag{18}$$

The force acting on the sphere is

$$-2\pi a^2 \int_{-1}^{1} \delta p \cdot s \cdot ds = -2\pi a^2 \int_{-1}^{1} \delta p \cdot P_1(s) \cdot ds$$

and this must be equal to the product of the mass of the sphere and its acceleration

$$M\frac{d(Ue^{i\omega t})}{dt}.$$

By reference to Eq. 14, the force equation now becomes

$$-2\pi a^2 \rho \int_{-1}^{1} (\phi + \psi) P_1(s) \cdot ds = MU, \qquad (R = a) \tag{19}$$

Next, Eqs. 15, 16, 17, and 10g are used to transform Eq. 19 into

$$-\frac{m}{a}(\phi_1 + \psi_1) = -\frac{m}{a}\left(\frac{3j(f_1 - f_1^*)}{2h} + A_1 f_1\right) = MU \tag{20}$$

in which

$$m = \frac{4\pi}{3}\rho a^3$$

is the mass of fluid displaced by the sphere, and the argument of f_1, f_1^* is ha.

The scattering coefficients A_n and the velocity of the sphere U are determined from Eqs. 18 and 20. Separating the various orders, the following are obtained

$$\left(\frac{d\phi_n}{dR} + \frac{d\psi_n}{dR}\right)_{R=a} = 0 \quad \text{for} \quad n \neq 1 \tag{21a}$$

$$\left(\frac{d\phi_1}{dR} + \frac{d\psi_1}{dR}\right)_{R=a} = -U \quad \phi_1 + \psi_1 = -\frac{MaU}{m} \quad (R = a). \tag{21b}$$

It is seen that only A_1 is affected by the motion of the sphere since there is no reference to U in Eq. 21a. These coefficients, with the exception of the first order, are therefore the same as those calculated by Lord Rayleigh. For example

$$A_0 = \frac{V}{jh}\,\frac{ha\cos(ha) - \sin(ha)}{1 + jha}\,e^{jha}.$$

According to Eqs. 20 and 8b, the first order Eq. 21b can be rewritten

$$\frac{U}{h} = A_1\left(f_0 + \frac{2}{ha}f_1\right) + \frac{3jV}{2h}\left(f_0 + \frac{2}{ha}f_1 - f_0^* - \frac{2}{ah}f_1^*\right)$$

$$-\frac{MaU}{m} = \frac{3jV}{2h}(f_1 - f_1^*) + A_1 f_1$$

in which the argument of f_0, f_1 and of their conjugates is ha. From these two equations, A_1 and U are calculated with the aid of Eq. 11a.

$$A_1 = \frac{3V}{h}\,\frac{\sigma(ha\cos(ha) - \sin(ha)) + \dfrac{3\sigma - 1}{6}(ha)^2\sin(ha)}{\sigma(1 + jha) - \dfrac{3\sigma - 1}{6}(ha)^2}\,e^{jha} \tag{22}$$

with

$$\sigma = \frac{1}{3}\left(1 + 2\frac{M}{m}\right)$$

and

$$U = \frac{Ve^{jha}}{\sigma(1 + jha) - \dfrac{3\sigma - 1}{6}(ha)^2}.$$

For very long waves ($ha \ll 1$) the scattering coefficient A_1 becomes

$$A_1 = \frac{V}{2h}(ha)^3 \quad \text{for} \quad \sigma \to \infty$$

$$A_1 = -\frac{V}{15h}(ha)^5 \quad \text{for} \quad \sigma = 1.$$

Thus, when $m = M$ ($\sigma = 1$) the first order scattering of long waves at a great distance from the sphere is of a smaller order of magnitude than zero order scattering which has the order of magnitude $(ha)^3$. Since higher orders contribute but little, the conclusion is that the scattering of long waves for the case $m = M$ is symmetrical. On the contrary, scattering by a stationary sphere ($M \gg m$) receives contributions of equal order of magnitude from zero order and first order harmonics; the pattern of scattering intensity is thus unsymmetrical as pointed out by Lord Rayleigh.

4. MOTION OF AN INFINITELY RIGID SPHERE IN ELASTIC SOLID MEDIA

In this section, the analysis of the motion of an infinitely rigid sphere in elastic solid media will be presented in some detail. However, certain purely algebraic transformations are sketched very briefly since an extended presentation would be rather tedious, and in addition would require a great deal of space.

An infinitely rigid sphere of radius a and mass M is imbedded in an elastic solid medium in such manner that the medium is constrained to follow the motion of the sphere at all points on its boundary. Plane longitudinal acoustic waves of frequency $\omega/2\pi$ are propagated in the elastic medium in a direction which is chosen as the $+z$ axis of a rectangular coordinate system with its origin at the center of the sphere. It is desired to determine the motion of the sphere and the scattering

coefficients. Even though the incident waves are longitudinal, both longitudinal and transverse components are present in the radiation scattered by the sphere.

The procedure may be outlined as follows: The elastic displacements in the medium and the force acting on the sphere are derived from two potential functions. The latter are then developed in series of spherical surface harmonics with coefficients to be determined from boundary conditions and from the dynamic equation of motion of the rigid sphere.

Under the conditions postulated above, the elastic displacements in the medium are axially symmetrical and have no azimuthal component. It is therefore possible to derive the components of elastic displacement from two potential functions $\phi+\psi$ and χ where ϕ is the potential of the undisturbed plane longitudinal waves. The rectangular components of elastic displacement u, v, w are given, according to Lamb,[5] by the equations

$$u = \frac{\partial}{\partial x}\left(\phi + \psi + \frac{\partial \chi}{\partial z}\right), \qquad v = \frac{\partial}{\partial y}\left(\phi + \psi + \frac{\partial \chi}{\partial z}\right),$$
$$w = \frac{\partial}{\partial z}\left(\phi + \psi + \frac{\partial \chi}{\partial z}\right) + k^2\chi \tag{23}$$

where ψ, χ satisfy

$$\nabla^2\psi + h^2\psi = 0, \qquad \nabla^2\chi + k^2\chi = 0 \tag{24}$$

with

$h = 2\pi/l$

l the wave length of longitudinal waves

$k = 2\pi/l_1$

l_1 the wave length of transverse waves

Let λ, μ be the elastic constants of the medium and ρ its density, then

$$(\lambda + 2\mu)h^2 = \omega^2\rho, \qquad \mu k^2 = \omega^2\rho. \tag{25}$$

The potential of the incident plane longitudinal waves is given by

$$\phi = \frac{V}{-jh}\, e^{-jhz} = \sum_{n=0}^{\infty} \phi_n P_n(s) \tag{26}$$

where V is the amplitude of displacement of the waves, and where, according to Eq. 9

[5] H. Lamb: Phil. Trans. Roy. Soc., 203, 1904, p. 31.

$$\phi_n = V(2n+1)j^n \frac{f_n^*(hR) - f_n(hR)}{2h}. \tag{26a}$$

f_n is defined by Eq. 7, and f_n^* is its conjugate complex. R, s are defined by

$$R^2 = x^2 + y^2 + z^2, \qquad s = z/R.$$

From Eq. 23, 24 it follows that the dilatation

$$\Delta = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = -h^2(\phi + \psi). \tag{27}$$

Because of axial symmetry and because there is no azimuthal component of elastic displacement, the latter has only two components in spherical polar coordinates, namely a radial component u_R and a tangential component u_T. The radial component is in the direction of the radius R, the tangential component of displacement is at right angles to R in a plane through the z-axis; it is taken positive in the direction towards $+z$. Transforming Eq. 23 into spherical polar coordinates gives, since

$$\frac{\partial}{\partial z} = s\frac{\partial}{\partial R} + \frac{q^2}{R}\frac{\partial}{\partial s}$$

the formulae

$$u_R = \frac{\partial}{\partial R}\left(\phi + \psi + \frac{s}{R}\frac{\partial \chi}{\partial R} + \frac{q^2}{R}\frac{\partial \chi}{\partial s}\right) + k^2 s\chi \tag{28a}$$

$$u_T = \frac{q}{R}\frac{\partial}{\partial s}\left(\phi + \psi + \frac{s}{R}\frac{\partial \chi}{\partial R} + \frac{q^2}{R}\frac{\partial \chi}{\partial s}\right) + k^2 q\chi \tag{28b}$$

where*

$$q^2 = 1 - s^2.$$

The next step in the analysis is to express the stress in the elastic medium in terms of ϕ, ψ, χ and then to calculate the force acting on the sphere. The stress components needed in the following are given by the well known expressions[6]

* In spherical polar coordinates $s = \cos\theta$, $q = \sin\theta$.

[6] A. E. H. Love: *Mathematical Theory of Elasticity*, 4th ed., Art. 69.

$$T_{xz} = \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right), \qquad T_{yz} = \mu\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right),$$

$$T_{zz} = \lambda\Delta + 2\mu\frac{\partial w}{\partial z}. \tag{29}$$

The force per unit area in the direction of $+z$ acting on an element of the surface of the sphere is

$$F_z = \frac{x}{R}T_{xz} + \frac{y}{R}T_{yz} + \frac{z}{R}T_{zz}. \tag{30}$$

This can easily be expressed in terms of u_R, u_T, R, s

$$F_z = \lambda s\Delta + \mu\left(2s\frac{\partial u_R}{\partial R} + q\frac{\partial u_T}{\partial R} + \frac{q^2}{R}\frac{\partial u_R}{\partial s} - \frac{q}{R}u_T\right).^{*} \tag{31}$$

The total force F acting on the sphere is obtained by integration of F_z over the surface of the sphere. Since F is a linear combination of contributions furnished by the two functions $\phi+\psi$ and χ, it may be written

$$F = 2\pi a^2\int_{-1}^{1} ds\cdot F_z = F(\phi+\psi) + F(\chi). \tag{32}$$

A similar decomposition employing the same notation will be carried out subsequently in calculating the displacements u_R, u_T. By a simple transformation of coordinates it follows from Eqs. 23, 29 and 30

$$F_z(\phi+\psi) = \lambda s(\phi+\psi) + \frac{2\mu s}{R}\frac{\partial}{\partial R}\left\{R\frac{\partial(\phi+\psi)}{\partial R} - (\phi+\psi)\right\} + \frac{2\mu q^2}{R^2}\frac{\partial}{\partial s}\left\{R\frac{\partial(\phi+\psi)}{\partial R} - (\phi+\psi)\right\}. \tag{33}$$

* Similarly $F_R=\lambda\Delta+2\mu\frac{\partial u_R}{\partial R}$, $F_T=\mu\left(\frac{q}{R}\frac{\partial u_R}{\partial s}+\frac{\partial u_T}{\partial R}-\frac{u_T}{R}\right)$. These expressions can be used to determine the scattering of plane waves by a spherical cavity in an infinite elastic medium. The boundary conditions in this case are $F_R=F_T=0$ for $R=a$. The zero order scattering coefficient, as defined later in Eq. 38, is given by $A_0=\frac{jV}{h}\frac{\frac{1}{2}(ka)^2\sin ha + ha\cos ha - \sin ha}{1+jha-\frac{1}{4}(ka)^2}e^{jha}$ which for long waves ($ha \ll 1$) becomes $A_0=\frac{1}{3}jVa^3(k^2-\frac{3}{2}h^2)$ an expression proportional to the modulus of compression of the elastic solid medium.

To obtain $F(\phi+\psi)$, Eq. 33 must be integrated with respect to s as shown by Eq. 32. The details need not be given; it seems sufficient to mention two operations which simplify the results, namely the use of Eq. 24 transformed to polar coordinates

$$\frac{\partial^2(\phi+\psi)}{\partial R^2}+\frac{2}{R}\frac{\partial(\phi+\psi)}{\partial R}+\frac{1}{R^2}\frac{\partial}{\partial s}\left(q^2\frac{\partial(\phi+\psi)}{\partial s}\right)+h^2(\phi+\psi)=0 \tag{34}$$

and repeated employment of partial integration with respect to s. A very simple formula is obtained in this way

$$F(\phi+\psi)=-(\lambda+2\mu)2\pi a^2h^2\int_{-1}^{1}s(\phi+\psi)\cdot ds \quad (R=a). \tag{35}$$

Similarly, from

$$F_z(\chi)=\frac{2\mu}{R}\frac{\partial}{\partial z}\left(R\frac{\partial^2\chi}{\partial z\partial R}-\frac{\partial\chi}{\partial z}\right)+\mu k^2\frac{\partial\chi}{\partial R}+\mu k^2 s\frac{\partial\chi}{\partial z} \tag{36}$$

simple transformations lead to

$$F(\chi)=\frac{4\pi a^2}{3}\mu k^2\int_{-1}^{1}ds\cdot(P_0-P_2)\frac{\partial\chi}{\partial R}-4\pi a\mu k^2\int_{-1}^{1}ds\cdot P_2\chi \quad (R=a) \tag{37}$$

where P_0, P_1, P_2 are Legendre polynomials in s.

In the preceding, only general coordinate transformations and Eq. 24 were employed. The next step in the procedure is the development of ψ, χ in series of spherical surface harmonics and the derivation of expressions for displacement and force in terms of the coefficients of the series. Since ψ, χ are solutions of Eq. 24

$$\psi=\sum A_n f_n(hR)P_n(s) \tag{38a}$$

$$\chi=\sum(2n+1)C_n g_n(kR)P_n(s) \tag{38b}$$

where identically

$$g_n(\xi)\equiv f_n(\xi).$$

The symbol g_n is not strictly necessary but it contributes greatly towards simplifying subsequent equations. In the following, the argu-

ment of g_n will always be kR or ka, whereas f_n will have the argument hR or ha. Since, except for argument, the g's are identical with the f's, they have the properties given by Eqs. 8a–8d, 11a.

From Eqs. 28a, 28b, 38a, 38b the series development of the elastic displacement components u_R, u_T are obtained. Separating the contributions of $\phi+\psi$ and of χ, it is a simple matter to derive

$$u_R(\phi+\psi) = h\sum(\phi_n' + A_n f_n')P_n(s) \tag{39a}$$

$$u_T(\phi+\psi) = \sum \frac{1}{R}(\phi_n + A_n f_n)Q_n(s) \tag{39b}$$

where

$$Q_n(s) = q\frac{d}{ds}P_n(s)$$

is an associated Legendre function.

To evaluate the χ components of displacement, use is made of relations given by Eqs. 8b, 8d, 10c and 10f to obtain

$$\frac{\partial\chi}{\partial z} = k\sum(nC_{n-1} - (n+1)C_{n+1})g_nP_n.$$

Then, employing Eqs. 8b, 8c and 10d

$$u_R(\chi) = -k^2\sum n(n+1)(C_{n-1}+C_{n+1})\frac{g_n}{kR}P_n \tag{40a}$$

and referring to Eqs. 8d and 10e

$$u_T(\chi) = k^2\sum(C_{n-1}+C_{n+1})\left(\frac{ng_n}{kR}+g_{n-1}\right)Q_n. \tag{40b}$$

It is seen that the scattering coefficients of longitudinal and transverse waves of the n-th order are respectively

$$A_n \quad \text{and} \quad C_{n-1}+C_{n+1}.$$

These coefficients must be determined from the boundary conditions and from the dynamic equation of motion of the sphere.

Collecting the terms of Eqs. 39 and 40, the following final formulae are obtained for the elastic displacement in the medium

$$u_R = \sum\left[h\phi_n' + hA_n f_n' - k^2 n(n+1)(C_{n-1}+C_{n+1})\frac{g_n}{kR}\right]P_n(s) \qquad (41a)$$

$$u_T = \sum\left[\frac{1}{R}(\phi_n + A_n f_n) + k^2(C_{n-1}+C_{n+1})\left(\frac{ng_n}{kR}+g_{n-1}\right)\right]Q_n(s). \qquad (41b)$$

The arguments of f_n, g_n in Eq. 41 are respectively hR and kR.

At the boundary of the rigid sphere ($R=a$)

$$u_R = UP_1(s), \qquad u_T = UQ_1(s)^* \qquad (42)$$

where U is the amplitude of the absolute motion of the sphere in space. Since only first order harmonics appear in Eq. 42, the coefficients of all other orders must vanish in Eq. 41 on the surface of the sphere. Hence these equations are sufficient to determine all scattering coefficients, except those of the first order. As an example, the zero order scattering coefficient of longitudinal waves is

$$A_0 = -\phi_0'/f_0' = \frac{V}{jh}\,\frac{\sin ha - ha\cos ha}{1 + jha}\,e^{jha}$$

which is the same as the corresponding scattering coefficient in the case of a rigid sphere in fluids.† The general expressions for the scattering coefficients—with the exception of the first order—are

$$A_n = \frac{\phi_n'(ng_n + kag_{n-1}) + n(n+1)\dfrac{\phi_n g_n}{ha}}{ng_n f_{n-1} - kag_{n-1}f_n'} \qquad (43a)$$

$$C_{n-1} + C_{n+1} = \frac{f_n'\phi_n - f_n\phi_n'}{k(ng_n f_{n-1} - kag_{n-1}f_n')} \qquad (43b)$$

where the arguments of the f_n's and of the g_n's are respectively ha and ka. The scattering coefficients given by Eq. 43 are clearly independent of the motion of the sphere; they will not be considered any further.

The force acting on the sphere is obtained by substituting Eqs. 38a, b in Eq. 35 and Eq. 37. Use is also made of Eq. 25 to express the elastic moduli λ, μ in terms of h^2, k^2. In this manner a simple expression is obtained for the total force acting on the sphere

* $P_1(s)=s=\cos\theta \qquad Q_1(s)=q=\sin\theta.$

† There is no zero order transverse scattering component since $Q_0\equiv 0$ in Eq. 41b, and $n(n+1)=0$ in Eq. 41a when $n=0$.

$$F = -\frac{m\omega^2}{a}(\phi_1 + A_1 f_1) + \frac{2m\omega^2}{a} k(C_0 + C_2) g_1 \tag{44}$$

with

$$m = \frac{4\pi}{3} a^3 \rho$$

which is the mass of the medium displaced by the sphere.

The force F is equal to the product of the mass of the sphere M and of its acceleration $d^2(Ue^{j\omega t})/dt^2$ which may be written

$$F = -M\omega^2 U \tag{45}$$

since the exponential factor $e^{j\omega t}$ has been omitted in all equations. The scattering coefficients of the first order A_1, C_0+C_2 are obtained from the following three first order equations derived from Eqs. 41, 42, 44 and 45:

$$\begin{aligned} \frac{maU}{M} &= \phi_1 + A_1 f_1 - 2k(C_0 + C_2) g_1 \\ aU &= \phi_1 + A_1 f_1 + k(C_0 + C_2)(g_1 + kag_0) \\ aU &= -2\phi_1 - 3jha\phi_0 - A_1(2f_1 + haf_0) - 2k(C_0 + C_2) g_1 \end{aligned} \tag{46}$$

in which the arguments of the f's and of the g's are respectively ha and ka. The solutions of Eq. 46 are

$$\frac{U}{V} = -\frac{g_1 + \frac{1}{3}kag_0}{h^2 a^2 D} \tag{47a}$$

with

$$D = f_1 g_1 + \frac{1}{9}\left(2 + \frac{M}{m}\right) ahf_0 g_1 + \frac{1}{9}\left(1 + 2\frac{M}{m}\right) kag_0 f_1 + \frac{1}{9}\frac{M}{m} hka^2 f_0 g_0$$

from which Eq. 3 is derived by substitution of the proper expressions for the f's and g's obtained from Eq. 11a. The first order scattering coefficients are

$$A_1 = \frac{\frac{1}{3}\left(\frac{M}{m} - 1\right) aU - (\phi_1 + jha\phi_0)}{f_1 + \frac{1}{3}ahf_0} \tag{47b}$$

$$C_0 + C_2 = \frac{\frac{1}{3}\left(1 - \frac{M}{m}\right) aU}{k(g_1 + \frac{1}{3}kag_0)} . \tag{47c}$$

More explicit expressions may be had by the use of substitutions from Eqs. 11a and 26a.

The special case $M = m$ merits a brief discussion. Eq. 47c shows that in this case

$$C_0 + C_2 = 0.$$

Hence there is no first order scattering of transverse waves in this special case. Further, Eq. 47a is reduced to a form identical with the corresponding Eq. 1 for the motion of a rigid sphere in fluids. At the same time, Eq. 47b for the first order scattering coefficient A_1 becomes identical, except for sign, with Eq. 22 of the fluid case; the difference in sign is due to the difference in the way in which displacement and velocity are derived from the respective potentials in the fluid and in the elastic solid case.

PATENTS*

ELECTRICAL PROSPECTING

U.S. No. 2,354,535. G. Muffly. Iss. 7/25/44. App. 10/11/40. Assign. Gulf Research & Development Co.

Electrical Prospecting. A method of electrical prospecting in which an a-c of one frequency is applied to the earth and electrically non-linear regions located with exploring electrodes connected to apparatus sensitive to other frequencies, or in which a-c of two frequencies are used and non-linear regions located by their modulation effect.

U.S. No. 2,358,027. C. J. Penther and F. B. Rolfson. Iss. 9/12/44. App. 1/26/42. Assign. Shell Development Co.

Electromagnetic Method and Apparatus for Pipe Line Surveying and Exploration. A method and apparatus for locating magnetic anomalies by means of two high permeability non-reactive conductors in the arms of a high frequency bridge and detecting the high frequency resistance unbalance produced near an anomaly.

GRAVIMETRIC PROSPECTING

U.S. No. 2,351,955. A. Graf. Iss. 6/20/44. App. 2/4/41 and 12/30/39. Vested in Alien Property Custodian.

Gravity Meter. A gravity meter of the type in which the moving system carries shutters which affect the amount of light falling on differentially connected photocells, construction permitting adjustment of the moving shutters and minimizing heat transfer to the apparatus from the light sources.

U.S. No. 2,355,421. D. H. Clewell and H. A. Maeder. Iss. 8/8/44. App. 8/6/41. Assign. Socony-Vacuum Oil Co. Inc.

Gravity Meter. A null reading horizontal pivoted beam type gravity meter having air damping, the null adjustment being made by means of a slide adjustment on the fixed end of a supporting spring.

U.S. No. 2,357,356. O. S. Petty. Iss. 9/5/44. App. 11/20/40.

Measuring Instrument and Method. A suspended mass type gravity meter in which the displacement is measured by the change in electrical capacity of movable plates, and having in the case for comparison a standard condenser and a condenser effected by temperature only, and providing temperature compensation by support bolts of two different metals whose effective lengths may be adjusted.

U.S. No. 2,357,822. A. F. Hasbrook. Iss. 9/12/44. App. 6/2/41. Assign. Olive S. Petty.

Measuring Instrument. A gravity meter clamping device having oppositely directed cones which are approached by screws on a split circular frame, the screws being adjustable to either clamp or allow a small clearance.

* Abstracts by O. F. Ritzmann, Gulf Oil Corporation Patent Department.

SEISMOGRAPH PROSPECTING

U.S. No. 2,352,494. J. O. Parr, Jr. Iss. 6/72/44. App. 7/21/42. Assign. Olive S. Petty.

Seismic Surveying. An avc circuit for seismograph amplifiers in which the control threshold is increased with time to prevent late strong reflections from actuating the control.

U.S. No. 2,352,869. J. F. Tolk. Iss. 7/4/44. App. 2/23/43. Assign. Olive S. Petty.

Seismic Surveying. A method of seismograph recording in which the detector output is simultaneously and separately recorded through two channels, one with filtering and one without.

U.S. No. 2,353,484. E. Merten and J. P. Woods. Iss. 7/11/44. App. 1/5/42. Assign. Shell Development Company.

Seismic Exploration Method. A method of generating seismic waves by exploding a confined gaseous explosive either inside the earth or on its surface and which covers an area whose dimensions are of the order of one-tenth the distance to the nearest reflecting horizon.

U.S. No. 2,353,920. D. S. Muzzey, Jr. Iss. 7/18/44. App. 5/30/42. Assign. Shell Development Company.

Vibration Detector. A device for detecting mechanical or acoustic vibrations by means of a small area electrode in contact with a liquid, relative motion between electrode and liquid causing variations in an applied electric current.

U.S. No. 2,354,420. J. P. Minton. Iss. 7/25/44. App. 12/16/37. Assign. Socony-Vacuum Oil Co.

Contractor-Expander for Electric Seismographs. A method of controlling the amplification of a seismograph amplifier as a function of time by means of two condenser discharge circuits acting on two separate grids, one of which decreases the amplification quickly and one which increases the amplification slowly, both effects being initiated by the time break impulse.

U.S. No. 2,354,548. N. H. Ricker. Iss. 7/25/44. App. 8/29/41. Assign. Standard Oil Development Co.

Seismic Prospecting. A method of seismic prospecting in which a long spread is used and the transverse wave generated by reflection at large angle of incidence is recorded.

U.S. No. 2,354,659. W. O. Bazhaw and J. O. Parr, Jr. Iss. 8/1/44. App. 6/13/42. Assign. Olive S. Petty.

Seismic Surveying. A method of seismic exploration by recording the spontaneous potential developed between two ground electrodes when the region is traversed by seismic wave.

U.S. No. 2,355,826. J. A. Sharpe. Iss. 8/15/44. App. 11/12/41. Assign. Stanolind Oil and Gas Co.

Seismic Prospecting. A method of eliminating variable distortion in reflection pulses resulting from transmission through the weathered layer by inserting in the seismic

channel a corrective network which is adjusted for correct compensation by means of a continuous wave generator applied to the ground.

U.S. Re. 22,535 (Orig. No. 2,317,334). E. J. Shimek. Iss. 8/22/44. App. 2/21/40 and 4/14/44. Assign. Socony-Vacuum Oil Co.

Master Control for Electric Seismographs. A control for seismograph amplifiers in which the shot moment, up-hole impulse, and first arrivals are all recorded on a regular trace and in which amplifier sensitivity is cut down by a delayed action shot moment relay and subsequently expanded as a function of time.

U.S. No. 2,359,245. O. F. Ritzmann. Iss. 9/26/44. App. 1/19/43. Assign. Gulf Research & Development Co.

Electrical Displacement Vibrometer. A long period geophone in which the mass displacement is indicated by the resistance change of a flexible resistance strip cemented to a cantilever suspension spring.

WELL LOGGING AND SURVEYING

U.S. No. 2,352,247. L. W. Blau and G. E. Cannon. Iss. 6/27/44. App. 6/4/38. Assign. Standard Oil Development Co.

Thermal Well-Logging. A thermal well logging apparatus which measures with a thermocouple recording at the surface the horizontal temperature gradient in the well fluid.

U.S. No. 2,352,433. G. Herzog. Iss. 6/27/44. App. 2/12/43. Assign. The Texas Co.

Well Logging. A method of increasing the sharpness with which a boundary is indicated on a well log by running a continuous log going into the well and also coming out and subtracting the two logs.

U.S. No. 2,352,993. M. M. Albertson. Iss. 7/4/44. App. 4/20/40. Assign. Shell Development Co.

Radiological Method of Logging Wells. A method of determining porosity of formations by forcing into the formation a fluid having a radioactive tracer, removing the fluid from the hole while maintaining pressure and then making a radioactivity log.

U.S. No. 2,353,435. W. J. Barnhart. Iss. 7/11/44. App. 6/16/41.

Side Sampler for Deep Wells. A side wall sampler in which the sample takers are forced outward by cams when the tool carrier is jarred downward with the housing resting on the bottom of the hole.

U.S. No. 2,353,619. B. Pontecorvo and G. Swift. Iss. 7/11/44. App. 9/18/41. Assign. Well Surveys, Inc.

Geophysical Prospecting. A method of locating the bottom of a hole in radiation logging by suspending a radiation source far enough below the detector so as not to disturb the latter, but having the connection sufficiently flexible so that the detector may be lowered onto the source when bottom is reached.

U.S. No. 2,354,399. W. B. Noble. Iss. 7/25/44. App. 5/4/42. Assign. Reed Roller Bit Co.

Side Hole Coring Device. A wire line operated side wall coring tool which locks to the drill stem and forces the core taker into the formation by fluid pressure.

U.S. No. 2,354,887. D. Silverman and R. E. Fearon. Iss. 8/1/44. App. 10/29/42. Assign. Stanolind Oil and Gas Co.

Well Signaling System. A method of signaling from the drill bit to the surface for logging while drilling or vice versa for control operations and consisting of a coaxial annular transformer core coupled to electrical equipment in the well, the drill stem and earth forming a single turn secondary whose current may be picked up at the surface by connection to the drill stem and a ground electrode.

U.S. No. 2,357,051. W. L. McLaine. Iss. 8/29/44. App. 6/10/40.

Drilling Speed Recorder. A drilling rate recorder in which the record strip has transverse lines whose length is a measure of the time required to drill unit distance and having a manual reset each time a new unit is started.

U.S. No. 2,357,177. H. G. Doll. Iss. 8/29/44. App. 12/12/39. Assign. Schlumberger Well Surveying Corporation.

Method and Apparatus for Conducting Different Investigations Simultaneously in Bore Holes. A method of simultaneously transmitting several electrical well logging signals over a single conductor cable by using different frequency generators in the well for each measurement and separating the signals with filters at the surface.

U.S. No. 2,357,178. H. G. Doll. Iss. 8/29/44. App. 12/13/39. Assign. Schlumberger Well Surveying Corporation.

Method and Apparatus for Investigating Bore Holes. A method of simultaneously making self potential and resistivity logs having several current electrode spacings over a single conductor cable by driving a motor generator in the well with power of one frequency, feeding the current electrodes with generated current of different frequencies, and separating the various potentials by filtered recording channels at the surface.

U.S. No. 2,357,907. R. A. Phillips. Iss. 9/12/44. App. 5/6/40. Assign. One-half to Mort L. Clopton.

Retractable Core Taking Device. A wire line core barrel which is held to the drill stem by fluid pressure and whose upper end is sealed by a sleeve valve when lifting force is applied by the wire line.

U.S. No. 2,358,441. M. C. Bowsky. Iss. 9/19/44. App. 7/12/41. Assign. Lane-Wells Company.

Inductive-Capacitive Electrical Logging. A method of electric well logging using a-c and having in the potential circuit a synchronous rectifier set 90° out of phase with the applied voltage so that potential indications are produced only when inductive or capacitive effects are present.

U.S. No. 2,358,470. W. N. Oswald, Iss. 9/19/44. App. 11/17/39. Assign. Houston Oil Field Material Co. Inc.

Sampling Device. A wire line operated side wall sampler to be run through the drill

stem and which engages a special section having a side opening, the sample being taken by a hinged tube forced into the formation by lowering the drill stem slightly when the sampler is in place.

U.S. No. 2,358,574. L. G. Howell. Iss. 9/19/44. App. 7/8/40. Assign. Standard Oil Development Co.

Gamma Ray Well Logging. A method and apparatus for gamma ray logging in which the ionization chamber current is fed to the grid of an electrometer tube and converted to a-c by periodically grounding the grid or by periodically varying a condenser across a grid resistor.

U.S. No. 2,358,945. C. F. Teichmann. Iss. 9/26/44. App. 8/31/40. Assign. Texaco Development Corp.

Method of Determining the Porosity and Location of Permeable Formations in Oil Wells. A method of locating permeable formations by removing the mud cake, filling the hole with a solution of radioactive material, applying pressure to force it into the formation and then removing the fluid and running a radioactivity log.

U.S. No. 2,359,067. R. Warren. Iss. 9/26/44. App. 10/21/40. Assign. Houston Oil Field Material Co., Inc.

Orienting Apparatus for Wells. A device for signaling by fluid pressure when a whipstock is correctly oriented and having a level ball which closes a solenoid contact, the solenoid releasing a valve which permits fluid to flow past a constriction which is previously dropped into the device.

MISCELLANEOUS

U.S. No. 2,345,535. W. L. Horner. Iss. 3/28/44. App. 1/3/38 and 7/6/42. Assign. Core Laboratories, Inc.

Method of Determining Porosity. A method of determining the porosity of a core sample by measuring its density, and with part of the sample determining the volume of gas filled pore space by forcing an incompressible liquid into it, and with another part of the sample distilling off and collecting the liquid content of the pores, and combining the results.

U.S. No. 2,351,079. H. M. Strobel. Iss. 6/13/44. App. 10/25/40.

Inertia Control System. A feedback system for electromechanical transducers, and having a secondary system in which the motion is analyzed for the acceleration component which is then amplified and fed back into the primary system.

U.S. No. 2,253,219. R. C. Olesen. Iss. 6/27/44. App. 10/7/41. Assign. Consolidated Engineering Corp.

Vibration Measuring System. An oscillator for carrier modulation type of vibration measurements and which is stabilized by using a glow discharge limiter in series with a tuned inverse feedback circuit.

U.S. No. 2,352,326. C. W. Kandle. Iss. 6/27/44. App. 10/29/42.

Earth Drill. An earth auger having a cylindrical bucket above the cutting edge and a partition to keep cuttings from interfering with earth entering at the cutter opening.

U.S. No. 2,352,638. F. C. Kelton, Jr. Iss. 7/4/44. App. 10/24/40. Assign. Core Laboratories, Inc.

Connate Water Determination. A method of determining the connate water in a formation, by cutting a core under mud pressure, bringing it to the surface while exposed to the mud, measuring the free water content, free gas content and fractional porosity, and from these measurements and empirical formulae computing the connate water content of the formation.

U.S. No. 2,352,835. K. L. Hertel. Iss. 7/4/44. App. 9/13/39. Assign. University of Tennessee Research Corp.

Apparatus for and Method of Determining Physical Properties of Porous Material. A device for measuring resistance to fluid flow by means of a fluid bridge circuit having an adjustable capillary in one arm and a manometer to indicate balance.

U.S. No. 2,352,836. K. L. Hertel. Iss. 7/4/44. App. 9/13/39 and 6/8/42. Assign. University of Tennessee Research Corp.

Method of and Apparatus for Determining Physical Properties of Porous Compressible Materials. A method and apparatus for measuring resistance to fluid flow, density and surface area per unit mass of compressible material by means of a fluid bridge circuit which is balanced by compressing the porous sample, and repeating the observations at a different degree of compression.

U.S. No. 2,353,211. T. Zuschlag. Iss. 7/11/44. App. 5/13/40. Assign. Magnetic Analysis Corp.

Electrical Analysis. An eddy current type flaw detector for rods or tubes and having energizing and pick-up coils which are small compared with the cross sectional dimensions of the test piece, and moving the test piece with rotation and translation so as to cover the entire material.

U.S. No. 2,353,249. M. P. Lebourg. Iss. 7/11/44. App. 5/19/42. Assign. Schlumberger Well Surveying Corp.

Tension Measuring Devices. A remote indicating cable tension indicator in which the cable is deflected against a flat leaf spring and nonlinearity is corrected by having the spring displacement operate a cam which turns a potentiometer shaft.

U.S. No. 2,355,128. F. W. Whitlock, U.S.A. Iss. 8/8/44. App. 3/19/42.

Measuring Device. An apparatus for measuring the displacement-time characteristics of a rapidly moving body and having an attached moving coil arranged so that it moves close to a series of stationary coils of alternate phase connected to an oscillator and recording the current picked-up by the moving coil.

U.S. No. 2,355,658. R. C. Lawlor, Iss. 8/15/44. App. 4/17/40. Assign. Consolidated Engineering Corp.

Method and Apparatus for Mass Spectrometry. A mass spectrometer having several ion collectors whose currents are fed through a balanced modulator and mixer to meters which indicate the concentration of the various ions.

U.S. No. 2,355,858. S. H. Hahn and R. H. Judson. Iss. 8/15/44. App. 10/17/41. Assign. The B. F. Goodrich Co.

Apparatus for Determining the Relative Porosity of Various Porous Materials. A portable device for testing the porosity of sponge rubber by drawing air through it, the instrument being made direct reading by having an orifice in series with the flow and also a mechanism for returning the indicator to zero when the motor is turned off.

U.S. No. 2,355,940. T. Zuschlag. Iss. 8/15/44. App. 11/23/40. Assign. Magnetic Analysis Corp.

Demagnatizing System. Apparatus for demagnetizing rods or bars and having two concentric coils through which the material is passed, one coil being a-c excited and the other having its induced current rectified to set up a unidirectional field.

U.S. Re. 22,531 (Orig. No. 2,277,756). D. G. C. Hare. Iss. 8/22/44. App. 6/26/40 and 4/22/44. Assign. The Texas Co.

Method and Apparatus for Measuring Thickness. A method of measuring thickness of pipe, etc., when having access to one side only by using penetrating radiation and measuring the intensity of scattering.

U.S. No. 2,356,145. S. J. Begun. Iss. 8/22/44. App. 6/12/40. Assign. Magnetone, Inc.

Magnetic Sound Recording and Reproducing. A magnetic tape recording and playback device having several sections and with controls for using it as a voice mirror and arranged so that the operator may select either some of his own or model reproductions.

U.S. No. 2,356,206. F. G. Boucher. Iss. 8/22/44. App. 2/25/41. Assign. Standard Oil Development Co.

Temperature Control Circuit. A temperature controller which is free from vibration chatter and in which the mercury column operates a sensitive relay and this in turn operates a time delay relay controlling the heating current.

U.S. No. 2,356,478. N. R. Stryker. Iss. 8/22/44. App. 7/25/42. Assign. Bell Telephone Laboratories, Inc.

Method of Acoustic Measurement. A method of measuring the acoustic absorption of a room by emitting a short pulse, measuring the relative energy density produced by the pulse at two points of different distance and computing the absorption from a theoretical formula.

U.S. No. 2,356,967–968. W. C. Barnes and H. W. Keevil. Iss. 8/29/44. App. 2/24/40 and 4/14/41.

Rail Flaw Detecting Apparatus. A magnetic pick-up unit for a rail flaw detecting device and having one pole wider than the other or having three poles one being wound with a coil and one displaced from this transversely and one longitudinally.

U.S. No. 2,357,617. P. Subkow and L. Dillon. Iss. 9/5/44. App. 2/1/43. Assign. Philip Subkow.

Geometrical Determination of Dip and Strike of Cored Strata. A method of determining dip and strike by taking from the same or parallel formations two cores of different known space orientation and geometrically finding a single plane which fits both cores.

U.S. No. 2,358,795. A. Djidics and C. D. Pratt. Iss. 9/26/44. App. 10/21/40. Assign. Atlas Powder Co.

Can Connector Device. An end coupling for connecting cans of explosive, each end of the can having openings and spirally shaped spring tongues which engage the openings of the next can when turned slightly.

U.S. No. 2,359,135. E. D. Lynton. Iss. 9/26/44. App. 3/13/42. Assign. Standard Oil Co. of California.

Method of Well Core Investigation. A method of determining dip and strike of a core by observing the stratification under ultraviolet light, marking the core and also determining its orientation.

U.S. No. 2,359,158. F. C. Rushing and M. P. Vore. Iss. 9/26/44. App. 2/12/42. Assign. Westinghouse Electric & Manufacturing Co.

Vibration Measuring Apparatus. A suspended magnet electrodynamic type vibration pick-up having attached to the magnet a separate damping device consisting of a resonant spring mounted mass damped in oil.

PUBLICATIONS RECEIVED

(The publications listed below were received since issuance of GEOPHYSICS for October, 1944, and are available for loan to the membership. Articles cited are those of particular interest to geophysicists.)

American Journal of Science, Vol. 242, Nos. 4, 9–11 (April, September–November, 1944), New Haven.

Bulletin of the Academy of Sciences of the Union of Soviet Socialist Republics, Vol. VIII, No. 1 ("On the Question of the Integration of the Gradients of Gravity," by A. D. Dubiago. In Russian, with brief English summary), 1944, Moscow.

Bulletin of the American Association of Petroleum Geologists, Vol. 28, Nos. 9–12 (September–December, 1944), Tulsa.

Economic Geology, Vol. XXXIX, Nos. 1, 3, 5 (January–February, May, August, 1944), Lancaster.

Geophysical Abstracts, 117 (April–June, 1944), Washington,

Independent Petroleum Association of America Monthly, The, Vol. XV, Nos. 5–7 (September–November, 1944), Tulsa.

International (Chemical and Export) Industry, Vol. 25, No. 10 (October, 1944), London.

Journal of Applied Physics, Vol. 15, Nos. 9–11 (September–November, 1944), Lancaster.

Journal of the Institute of Petroleum, Vol. 30, Nos. 246–249 (June–September, 1944), London.

Petroleum, Vol. VII, Nos. 8–10 (August–October, 1944), London.

Proceedings of the Cambridge Philosophical Society, Vol. 40, No. 2 (June, 1944), Cambridge.

Publicaciones del Instituto de Fisiografia y Geologia:

XX. *Consideraciones Generales Sobre los Terremotos de la Argentina*, by Pierina Pasotti. Rosario, Argentina, 1944.

XXI. *Anotaciones Preliminares con Motivo de una Visita a la Ciudad de San Juan a Proposito del Terremoto del 15 de Enero de 1944*, by Alfredo Castellanos. Rosario, 1944.

Review of Scientific Instruments, The, Vol. 15, Nos. 8–10 (August–October, 1944), Lancaster.

Revista de Ciencias, Vol. XLVI, Nos. 447, 448 (March, June, 1944), Lima, Peru.

World Petroleum, Vol. 15, Nos. 10, 11, 13 (September, October, December, 1944), New York.

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GLENN M. MCGUCKIN received the B.S. degree in Physics from the University of Illinois in 1928, and later did graduate work at the University of Oklahoma. Following seven years in business and the teaching profession he took up seismograph work in 1935. The past seven years he has been with Magnolia Petroleum Company, Geophysical Division. He is a member of the Society of Exploration Geophysicists.

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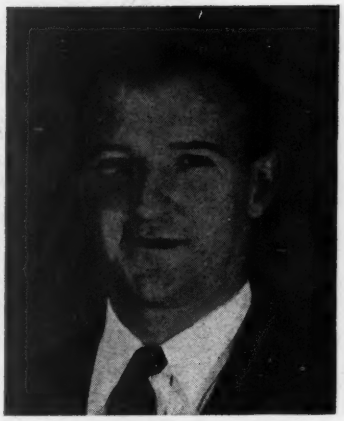
WYNNE K. HASTINGS

WYNNE K. HASTINGS received the B.A. degree from Oberlin College in 1926. He was employed by the Gypsy Oil Company in torsion balance exploration for the greater part of the years 1928–36. Since 1936 he has been engaged in seismic and gravimeter exploration for the Gulf Research & Development Company.

WM. BRADLEY LEWIS received his B.A. from Williams College in 1927. He spent six years at Caltech as assistant, and teaching fellow in chemistry, receiving his Ph.D. in 1933. He was employed for eight months in research on means to control penicilia mold on oranges. From 1934 to 1941 he was employed by the Humble Oil and Refining Company in geophysical and production research. He left Humble in 1941 to join The Elflex Company as president. He is a member of the Society of Exploration Geophysicists, and the American Institute of Mining and Metallurgical Engineers.

WM. BRADLEY LEWIS

ROBERT E. SOUTHER worked in the drilling department of McDannald Oil Company until he returned to the University of Texas in 1935. He received his B.S. degree in Petroleum Production Engineering from Texas in 1939. He was employed by Baroid Sales Division, National Lead Company as a well logging engineer when mud analysis logging was introduced to the petroleum industry. Since 1941 he has been well logging research and development engineer for Baroid Well Logging Service.



ROBERT E. SOUTHER

Photographs and biographies of contributors to this issue not appearing above have been published previously, as follows: SIGMUND HAMMER, Vol. VIII, No. 1, p. 73 (Jan. 1943); L. L. NETTLETON, Vol. VII, No. 3, p. 329 (July, 1942); ALFRED WOLF, Vol. VII, No. 4, p. 428 (Oct. 1942).

MEMORIAL

RICHARD H. FRETTER (1919–1944)

Richard H. Fretter was born May 29, 1919, in Los Angeles County, California. He passed away on March 9, 1944, after having been ordered to bed by his physician in December, 1943. He is survived by his wife, Geraldine Fretter, whom he married March 7, 1943, and by his mother, Mrs. Dorothy B. Fretter, of Pasadena, California.

Dick Fretter graduated from Pasadena, California, High School in 1938, and attended the University of California, Berkeley, California, until 1941. His majors were Mechanical Engineering and Mathematics. He worked while attending the University. He became proficient enough in the sport of fencing to coach during the first semester of 1940.

His employment with United Geophysical Company began in November, 1941, as Assistant Computer on a seismograph crew in California. In January, 1943, he became Chief Computer. At the time of his forced retirement, he was doing research in the company laboratory on the design of special seismograph equipment for water work.

Dick was an excellent teacher when he was Chief Computer, and his manner of presentation was studied and patient. His work was refined and polished and his practice of accuracy was exemplary. He was always friendly, good-natured and cooperative in every respect. The friendship he extended was always genuine and unqualified.

His passing is a loss to the company, to his friends and to the profession.

CHARLES E. RIDDELL
Brownfield, Texas

THE SOCIETY ROUND TABLE

ANNOUNCEMENT OF THE FIFTEENTH ANNUAL MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

In compliance with O.D.T. regulations concerning war-time meetings involving use of transportation facilities by 50 or more persons, the concurrent meetings of the S.E.G., A.A.P.G., and S.E.P.M., which were scheduled to be held in Tulsa March 20–22, have been cancelled by the governing bodies of the three organizations. The A.A.P.G. will hold a meeting of its officers and business committee only in Tulsa April 27.

The Executive Committee of the Society of Exploration Geophysicists, conscious of the importance of geophysical exploration in the discovery of new fields which are providing oil essential to the prosecution of the two wars in which our country is engaged, but wishing to observe the spirit and letter of the O.D.T. regulations, has decided on the following course of action.

1. The concurrent general meeting previously planned for March 20–22 in Tulsa is cancelled.

2. Two or more one-day local meetings will be held, in Tulsa, Houston, and such other localities as may express a desire to hold such a meeting.

3. The Tulsa meeting, to be held on Wednesday, April 4, is designated as the official technical and business meeting of the Society for the year 1945–46. No member or non-member whose presence at the meeting would involve the use of transportation facilities and/or hotel accommodations is invited or expected to attend, *except* the following:

a. Officers of the Society, constituting the Executive and Business Committees; the Business Manager; the District Program Committee Chairman; and the candidates for office for the year 1945–46—a total of fifteen persons.

b. Members of the Society who have prepared technical papers for presentation in person at the technical sessions. It is anticipated that there will be a maximum of fifteen out-of-Tulsa members in this classification.

The Society has approximately 150 members in Tulsa whose presence at the meeting, along with that of some portion of the 350 geologists resident in Tulsa who will be interested in attending the technical sessions, will constitute an audience sufficient to guarantee an interesting and well-rounded discussion of each technical paper presented.

4. Approximately one week after the Tulsa meeting a local meeting will be held in Houston, to be attended only by geophysicists and interested geologists resident in Houston, at which the papers presented in Tulsa will be read *in absentia*, and the discussion of them summarized, and papers prepared by Houston authors will read in person. Thereafter these papers will be available in any locality where there is a desire to hold a similar meeting, by application of the regional Program Committee Chairman to the General Chairman of the Program and Arrangements Committee.

Henry C. Cortes, Vice-President of the Society, is General Chairman of the Program and Arrangements Committee. He is assisted by a Tulsa Arrangements Committee of the following composition: T. A. Manhart, Seismograph Service Corporation, 712 Kennedy Building, Tulsa 3, as chairman, George E. Wagoner, Carter Oil Company, Box 801, Tulsa 2, vice-chairman, A. I. Innes, Homer C. Moore, Stanley W. Wilcox; by a Tulsa Program Committee of the following composition: L. Y. Faust, Chairman, Geophysical Research Corporation, Box 2040, Tulsa 2, Oklahoma, R. Clare

Coffin, Vice Chairman, P. S. Williams, Albert J. Barthelmes, Joseph A. Sharpe, Advisory Member; and by the following areal Program Committees:

Houston—R. S. Jackson, Chairman, Independent, Exploration Company, 901 Esperson Building, Houston, Texas; Darryl S. Hughes, Albert L. Ladner, Roy L. Lay, W. J. Osterhoudt, J. C. Pollard.

Dallas—Cecil H. Green, Chairman, Geophysical Service, Inc., 1311 Republic Bank Building, Dallas 1, Texas; E. D. Alcock, W. W. Newton.

Pittsburgh—L. L. Nettleton, Chairman, Gulf Research & Development Co., Box 2038, Pittsburgh 30, Pennsylvania; Milton B. Dobrin, James M. Kendall.

Pacific Coast—O. C. Lester, Jr., Chairman, Amerada Petroleum Corporation, 552 Subway Terminal Building, Los Angeles 13, California; H. R. Thornburgh, Phil P. Gaby.

San Antonio—P. E. Narvarte, Chairman, Petty Geophysical Engineering Co., Box 2061, San Antonio 6, Texas; John F. Imle, Frederick E. Romberg.

New York-New England—R. F. Weichert, Jr., Chairman, Standard Oil Co. of New Jersey, 30 Rockefeller Plaza, New York City.

Fort Worth-Colorado—John H. Wilson, Chairman, Independent Exploration Company, 2210 Fort Worth Natl. Bank Bldg., Fort Worth 2, Texas; James L. Morris.

Any member of the Society who may be able to prepare a paper for presentation in person or by title at the meeting and for subsequent publication in GEOPHYSICS should communicate this information immediately to his local program chairman, or to the general chairman of the program and arrangements committee.

NOMINEES FOR 1945–1946 EXECUTIVE COMMITTEE

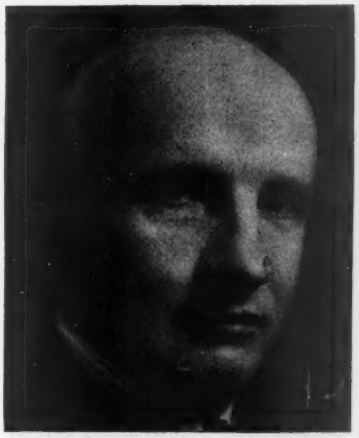
The following brief biographical sketches are presented in an attempt to acquaint members of the Society with nominees appearing on the official ballot for the coming year.

FOR PRESIDENT

HENRY C. CORTES attended the University of the South, at Sewanee, Tennessee. In February, 1922, he entered the oil business, starting as a roughneck on a rotary drilling rig at the Hull Salt Dome Field, Liberty County, Texas. This experience further stimulated his interest in exploration geology, an interest in which he was very materially aided through acquaintance and friendship with Wallace E. Pratt, the late E. T. Dumble, Alexander Deussen, the late L. P. Garrett, Dilworth S. Hager, L. P. Teas, and others. In 1924 he was employed in the Vacuum Oil Company's Geological Department. Convinced that geophysics was to play a leading role in finding new fields, he became keenly interested in the early torsion balance and refraction seismograph work and interpretation. Soon after he was placed in charge of Vacuum's geophysical crews, consisting of torsion balance and refraction parties, Geophysical Research Corporation introduced the reflection seismograph; upon his recommendation, some of the earliest work of this nature was done for Vacuum. When the Magnolia Petroleum Company merged with Vacuum, with formation of the Socony-Vacuum Oil Company, he was placed in charge of Magnolia's geophysical exploration, in which capacity he is still employed. He has had a major role, through geological and geophysical interpretation, in locating a number of oil and gas fields, among them Iowa, Cameron Meadows, Roanoke, Woodlawn, and West Gueydan in the Louisiana Gulf Coast, and Seeligson, La Gloria, and Tomball in the Texas Gulf Coast. He is a member of the American Association of Petroleum Geologists, President of the Dallas Petroleum Geologists and a member of the Houston Geological Society, the Dallas Petroleum Club, the American Geophysical Union, and the Society of Exploration Geophysicists, in which

he has been serving as a member of the War Efforts Advisory Committee and, this past year, Vice-President.

GERALD H. WESTBY was born in Stoughton, Wisconsin, of Norwegian-English parents, Julius A. Westby and Harriet Holinbeck Westby, on August 4, 1898. He was educated at the La Crosse, Wisconsin, grade and high schools, and was graduated from the latter in 1916. He later attended the University of Chicago and, influenced by Professor R. D. Salisbury, majored in geology, graduating in 1920. Partial credit was given for service in the Coast Artillery Officers Training School at Fort Monroe, Vir-



HENRY C. CORTES

GERALD H. WESTBY

ginia, where a commission as Second Lieutenant was received. In the summer of 1920, he taught Physiography and Geography at the University of Montana, leaving early in the fall to accept a position with S. Pearson & Son, of London, England. From late 1920 to early 1924, he served as Resident Geologist for this firm in Algeria. Following three months of research at Stanford University, he accepted a position as Field Geologist with the Empire Oil and Refining Company, with field headquarters at Denver, Colorado. In the fall of 1926 and in early 1927, while still employed by this company, he attended the first courses in geophysics to be offered at the Colorado School of Mines. In late 1927, he was made Chief Geophysicist of the Empire Oil and Refining Company (now Cities Service Oil Company), and remained in that position until September, 1933, when he joined the Seismograph Service Corporation. Since 1935 he has served as President of Seismograph Service. In 1930 he was the Mid-Continent representative of the Founding Committee of three members which originated the Society of Exploration Geophysicists, and he has served the Society as Secretary-Treasurer and as Vice-President (three terms). He is a member of the American Association of Petroleum Geologists, the American Institute of Mining and Metallurgical Engineers, and the Society of Exploration Geophysicists.

FOR VICE-PRESIDENT

JOHN JAY JAKOSKY was born at Vinita, Indian Territory (later Oklahoma) January 20, 1896. He received a B.S. in Mechanical Engineering at the University of Kansas in 1920, a B.S. in Electrical Engineering at the University of Pittsburgh in 1925, the Professional degree of Mechanical Engineer at the University of Kansas in 1926, and,

after graduate work at the Carnegie Institute of Technology and the University of Arizona, a Doctor of Science degree from the latter in 1933. From 1920–25 he acted as Research Engineer for the U. S. Bureau of Mines, chiefly in studies of underground communication, sub-surface attenuation, and similar matters. From 1925–28 he occupied the position of Physicist for the Western Precipitation Company and the Research Corporation, engaged principally in devising equipment for eliminating radio interference caused by high voltage precipitators. For a period of two years he served as a Consulting Engineer for the Southwestern Engineering Corporation, investigating high

JOHN JAY JAKOSKY

HENRY SALVATORI

frequency inductive methods for shallow mineral exploration. In 1929 he organized International Geophysics, Inc. In 1940 he resigned as President of International Geophysics to accept the position of Dean of the Schools of Engineering and Architecture and Director of the Engineering Experiment Station at the University of Kansas. In 1943 he accepted his present position as Director of Industrial Research and Assistant to the President of the University of Southern California. On leave, his present activities are devoted almost wholly to research concerned with the war. He is the author of the text EXPLORATION GEOPHYSICS, and is a member of the American Institute of Mining and Metallurgical Engineers (serving as a member of the Committee on Geophysics, the Committee on Geophysics Education, and the Committee on Mining Education), the American Association of Petroleum Geologists, the American Geophysical Union, the Society for the Promotion of Engineering Education, and the Society of Exploration Geophysicists. Academic organizations include Sigma Xi, Tau Beta Pi, Sigma Gamma Epsilon, Pi Tau Sigma, Theta Tau, and Delta Upsilon.

HENRY SALVATORI received the degree of B.S. in Electrical Engineering from the University of Pennsylvania in 1923, and the degree of M.A. in Physics from Columbia University in 1926. He was employed by the Bell Telephone Laboratories from 1923 until 1926, at which time he joined the Geophysical Research Corporation as Party Chief of one of the first experimental reflection seismograph parties. In 1929 he joined Geophysical Service, Incorporated, and in 1932 he organized the Western Geophysical Company. He has served as President of that organization since that time. He is a member of the Society of Exploration Geophysicists, the American Association of

Petroleum Geologists, the American Geophysical Union, the Seismological Society of America, and the American Association for the Advancement of Science.

FOR EDITOR

L. L. NETTLETON received his B.S. degree from the University of Idaho in 1918 and his Ph.D. degree from the University of Wisconsin in 1923. From 1923 to 1928 he was engaged in electrical work in the research department of the Union Switch & Signal Company at Swissvale (Pittsburgh), Pennsylvania. Since 1928 he has been in the re-

L. L. NETTLETON

NORMAN RICKER

search laboratory of the Gulf Oil Corporation, where he has had charge of the interpretation and mapping of gravity results (torsion balance, pendulum, and gravimeter). Also he has done some work in dynamic geology which is best known through his fluid mechanical concept and fluid models of the formation of salt domes. For some ten years he has been a member of the faculty of the University of Pittsburgh and has given a course of lectures on geophysical prospecting, the material of which was recently published in book form as "GEOPHYSICAL PROSPECTING FOR OIL." He is a member of the American Physical Society, American Association of Petroleum Geologists, American Geophysical Union, American Association for the Advancement of Science, Pittsburgh Physical Society, and a member of the Society of Exploration Geophysicists.

NORMAN RICKER received his B.A. degree in 1916, his M.A. in 1917, and his Ph.D. in 1920—all in Physics—from the Rice Institute. After an instructorship in Physics at Rice and two years with the Bell Telephone Laboratories in New York City, Dr. Ricker actively entered the field of geophysics. Employed in 1923 by the Humble Oil and Refining Company, he organized and directed their Geophysical Department, contributed to the development of refraction seismic prospecting, and introduced the use of radio in such operations. Resigning from the Humble Company in 1925, he worked independently in geophysics as a Consultant in a number of geophysical operations. In 1927 he was engaged by the Hughes Tool Company to develop the Plunger Lift. In 1938 Dr. Ricker accepted a position as Senior Research Geophysicist with The Carter Oil Company, where he is now employed at the research center in Tulsa. He is engaged in further development of seismic processes and in mathematical researches on the Wavelet Theory of Seismogram Structure. Among Dr. Ricker's accomplishments at the telephone laboratories was the invention of the paper cone type loud

speaker which displaced the horn type. He holds membership in the American Association for the Advancement of Science, the American Physical Society, the American Mathematical Society, the Acoustical Society of America, the American Geophysical Union, and the Society of Exploration Geophysicists.

CECIL H. GREEN

FREDERICK ROMBERG

FOR SECRETARY-TREASURER

CECIL H. GREEN received the degrees of S.B. and S.M. in Electrical Engineering in 1924 from the Massachusetts Institute of Technology. Until 1926 he was a development engineer in the A. C. Engineering Department, General Electric Company, Schenectady. During this period he also served as an instructor in advanced engineering classes. He then became Research Engineer for Raytheon Manufacturing Company, engaged in the development of Gaseous Discharge rectifier devices. In 1928 he became Development Engineer with Federal Electric Company, finally being placed in charge of the transmitting tube division of the Newark plant. He entered Geophysical Service, Incorporated, in 1930, serving as party chief until 1936 and as district supervisor until 1941, when he was made Vice-President. He is a member of the American Association of Petroleum Geologists and of its National Committee on Applications of Geology, Vice-President of the Dallas Petroleum Geologists, and a member of Dallas Petroleum Club and the Society of Exploration Geophysicists.

FREDERICK ROMBERG received his B.A. degree from the University of Texas in 1929, and his A.M. in Physics from Harvard in 1932. He spent the year 1929–30 in the geophysical department of the Humble Oil and Refining Company, and 1932–33 as a tutor in the Physics Department at Harvard. In 1933 he was employed by Geophysical Service, Inc. He was for some years chief of a seismograph field party, and later worked on the development and application of new interpreting methods, especially with respect to horizontal changes in seismic velocities. At present he is on leave of absence from Geophysical Service, Inc. and is engaged in maintenance and development of gravity meters in the LaCoste-Romberg laboratories. He is a member of the Seismological Society of America, Sigma Xi, and of the Society of Exploration Geophysicists.

The ballot reprinted below has been mailed to all active members of the Society of Exploration Geophysicists. Those who failed to receive copies may secure them by notifying J. F. Gallie, Business Manager at P.O. Box 410, El Dorado, Arkansas. *Only active members who have paid 1945 dues are eligible to vote.*

OFFICIAL BALLOT

FOR THE YEAR MARCH, 1945—MARCH, 1946

For the Election of Officers for the

SOCIETY OF EXPLORATION GEOPHYSICISTS

Before voting, please note the following extracts from the Society Constitution:
Article V-A—Officers

1. **The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. These, together with the Past President, shall constitute the Executive Committee and managers of the Society. Officers shall be elected for a term of one year with the exception of the Editor, who shall be elected for a term of two years.**

2. **. . . Each member shall cast one vote for each officer to be elected and shall return his ballot to the Secretary-Treasurer. Ballots to be valid must be enclosed in an envelope carrying on the outside the written signature of the member submitting the ballot, and must be received by the Secretary-Treasurer at his officially recognized address not later than ten days prior to the Annual Meeting. Only ballots received from Members in good standing as of a date ten days prior to the Annual Meeting shall be valid. . . .**

FOR PRESIDENT

HENRY C. CORTES	☐
G. H. WESTBY	☐
.....	☐

FOR VICE-PRESIDENT

J. J. JAKOSKY	☐
HENRY SALVATORI	☐
.....	☐

FOR EDITOR

L. L. NETTLETON	☐
NORMAN RICKER	☐
.....	☐

FOR SECRETARY-TREASURER

CECIL H. GREEN	☐
FREDERICK ROMBERG	☐
.....	☐

(Brief biographies of the nominees will appear in GEOPHYSICS for January.)
After voting, place in accompanying official envelope, which should then be signed and mailed to the

SECRETARY-TREASURER
W. HARLAN TAYLOR
1449 Mellie Esperson Bldg.
Houston 2, Texas

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

John Bemrose
F. Goldstone, L. E. Deacon, L. K. Mower
William Mitchell Erdahl
A. J. Barthelmes, G. E. Wagoner, T. A. Manhart
Alfred William Farmilo
A. E. Storm, F. A. Hale, R. L. Augenthaler
Fred Travis Ferguson
Hart Brown, L. H. Boyd, C. Sheldon Sharpe
George Murray Giltinan
A. J. Barthelmes, G. H. Westby, T. A. Manhart
Ronald Nelson Gsell
Paul E. Nash, D. J. Wolff, Wm. C. Woolley
Hubert Charles Guyod
W. M. Rust, Jr., J. B. Eby, Paul Weaver
Marion King Hubbert
F. Goldstone, L. K. Mower, L. W. Blau
Woodrow W. Lamkin
J. R. Johnson, V. L. Jones, G. L. Taylor
Junius Ovid Laws
A. I. Innes, Albert W. Taylor, John L. Ferguson
Willard Thomas Nutt
R. C. Herron, W. J. Osterhoudt, Paul C. Reed
Gwendolyn Peabody
Sidon Harris, R. H. Dana, P. H. Ledyard
Donald Arthur Peachee
J. B. Lovejoy, E. E. Unger, D. L. Scott
Van Alvin Petty, Jr.
W. Harlan Taylor, John F. Imle, P. E. Navarte
James Richardson Randolph
W. Hafner, F. Goldstone, L. K. Mower
Hugo Raymond Renden
John E. Futral, L. A. Scholl, Jr., Roy L. Lay
Dallas Leon Russell
O. T. Lawhorn, M. C. Kelsey, Cecil H. Green
Clarence Bill Scott
Norman Ricker, R. S. Dahlberg, Jr., F. G. Boucher
Arthur Leland Snow
W. Harlan Taylor, W. Lee Moore, Homer Roberts
Simeon Brooks Stewart
C. C. Zimmerman, H. W. McDonnold, J. H. Deming

Thomas Clifton Stotler
V. L. Jones, J. R. Johnson, R. C. Coffin
William Russell Sype
Joseph A. Sharpe, Neil R. Sparks, Garvin L. Taylor
Robert Treat Paine Thompson
Eugene McDermott, C. H. Green, H. B. Peacock
Dale Edward Turner
T. E. Dennis, Arthur B. Nomann, Frank Ittner

ASSOCIATE

Price Cawthorne Barbour
E. A. Eckhardt, George B. Lamb, W. J. Osterhoudt
Arnold Earle Brayton
Lawrence I. Freeman, L. Vincent Miller, Cecil E. Chesher
Joe Lee Ferguson
Hart Brown, C. Sheldon Sharpe, L. H. Boyd
Frederick William George
Hart Brown, C. Sheldon Sharpe, S. K. Van Steenbergh
Huston T. Jones, Jr.
V. L. Jones, J. R. Johnson, G. L. Taylor
Clarence Gayland Norris
Hart Brown, C. Sheldon Sharpe, L. H. Boyd
Ignaz Warren Russek
W. M. Tottenham, J. C. Menefee, Paul E. Nash
Tom F. Southgate
Arland I. Innes, R. H. Burton, John L. Ferguson
Millard Lafayette Suggs
F. L. Yeates, D. F. Broussard, R. S. Jackson
William Day Waldrep
V. L. Jones, J. Rudolph Johnson, R. C. Coffin

RESULTS OF BALLOT ON EDITOR'S TERM OF OFFICE

(Through oversight this announcement was omitted from the October, 1944 issue of GEOPHYSICS.)

On July 21, 1944, the following count was made of ballots submitted in connection with the proposed change in the Editor's term of office from three years to two:

Members approving the change	357
Members opposed	15
Votes discarded (no signature)	3
Total votes cast	375

In accordance with the results of this balloting, the third sentence in Section V-A-1 of the Society Constitution is hereby altered to read "Officers shall be elected for a term of one year with the exception of the Editor, who shall be elected for a term of two years."

W. Harlan Taylor,
Secretary-Treasurer

PERSONAL ITEMS

DONALD C. BRADFORD, formerly a Physicist with the U. S. Signal Corps at Ft. Monmouth, N. J., is now Special Projects Resarch Engineer with the Holtzer-Cabot Electric Co., 400 Stuart St., Boston, Mass. His residence address is Apt. 114, 50 Follen St., Cambridge 38, Mass.

MAJOR B. B. HUNKAPILLER has been transferred from Ft. Sill, Okla., to 477th F. A. Obsn. Bn., North Camp Hood, Texas.

RICHARD WILLIAMS has left the National Geophysical Co. of Dallas to become associated with the Seismic Engineering Co., also of that city. His current address is 404 Crockett Rd., Palestine, Texas.

JAMES A. SMITH, of the United Geophysical Co., is returning from South America and will be located at 2850 Telegraph Ave., Berkeley 5, Calif.

WILLIAM A. DRENNAN has moved from Berkeley to 200 Woodrow Ave., Oildale, Kern County, Calif.

SEAMAN FIRST CLASS (RT) ALBERT W. MUSGRAVE, who joined the Navy shortly after becoming a student member of the Society, has advised of his transfer from Houston to San Francisco. He may be addressed in care of Co. 60 (RMS), Naval Training School, T. I., San Francisco, Calif.

EDWARD D. LYNTON has returned to the States following eighteen months overseas with the Foreign Economic Administration and is again working for the California Research Corp., a subsidiary of Standard Oil of California. Headquarters are at 200 Bush St., San Francisco. Mr. Lynton's foreign duties were primarily concerned with the rehabilitation of mines and industries in French North Africa, thereby making use of his engineering experience.

M/SGT. E. GLENN ALBRIGHT, Army Serial No. 3402 8934, should be addressed at APO 17663, c/o Postmaster, New York, N. Y.

H. L. SCHIFLETT has moved from Leesburg to Gainesville, Fla., where his postal address is Box 196.

MURRELL HOLBERT, newly elected to the Society, has left the States for duty with the Richmond Petroleum Co., Edificio Sanper Brush, Bogota, Colombia, S. A.

R. G. SOHLBERG has been transferred from the South Mediterranean Oilfields, Ltd., Cairo, Egypt, to the Richmond Petroleum Co. of Colombia, with the mailing address Aptdo. Nac. 2760 (Aptdo. Aereo 3631), Bogota, Colombia, S. A.

AUSTIN N. STANTON, who has been serving as Associate Professor of Electrical Engineering at S. M. U. the past several years, has resigned to become Research Director of the Petroleum Science Laboratories, 2802 Greenville Ave., Dallas 6, Texas.

MAJOR LYNN D. ERVIN, after thirty-two months overseas duty with the Marines in the Pacific, has returned to the States. He has been assigned to the Officers' Base Defense School, Camp Lejeune, North Carolina, as an Instructor, and may be addressed in care of the Base Art'y Bn., T. C., at that location.

CLYDE H. WILSON, Independent Mining Engineer and Geophysicist, has left Gold Hill, Utah, to take up residence in Beverly Hills, Calif. His mailing address is Box 1263.

WILLIS H. FENWICK is Divisional Manager for the Brown Geophysical Co., P.O. Box 319, Casper, Wyoming.

J. G. FERGUSON, who has been serving at the Naval Ordnance Laboratory in Washington, D. C. for the past few years, has accepted a position as Gravity Supervisor with the Western Geophysical Co. His present address is 624 Hawthorne, Houston, Texas.

WALTER C. BONETBRAKE, who has recently elected to membership, is serving on Geophysical Party 2, the Atlantic Refg. Co., P.O. Box 2819, Dallas, Texas.

MICHAEL ALLON, of the Gulf Res. and Dev. Co., has returned from Pincher Creek, Canada, to the United States. His mailing address, as before, is P.O. Drawer 2038, Pittsburgh 30, Pa.

CAPT. J. B. BATSON has been transferred from Camp Bowie, Texas, to Hq and Hq Co., 847th STB, UC ASFTC, Camp Crowder, Mo.

ROBERT L. GEYER is now serving as Loftsman with the Rohr Aircraft Corp., Chula Vista, Calif. His residence address is 233 Del Mar Ave. in that city.

LT. GEORGE C. MCGHEE has returned to Washington, D. C., from Dallas. His address is 3100 P St., NW, Washington 7.

SAM ZIMERMAN, Party Chief for the Carter Oil Co., has moved from Douglas to Newcastle, Wyoming. His mailing address is Box 100.

LT. S. C. STONEHAM, USNR, may be addressed at 4861 Bancroft Drive, La Mesa, Calif., where he has been transferred from Texas.

R. J. MCGANN, Party Chief for the Western Geophysical Co., has been transferred from Bakersfield, Calif., to Montana. He may be addressed at P.O. Box 207, Roundup, Montana.

TUN YIN CHANG, formerly of the National Geophysical Co., is now Chief Computer for the Atlantic Refg. Co. He is currently located at Hammond, La., where his postal address is Box 749.

NEAL CLAYTON has left the Magnolia Pet. Co. to accept a position as Party Chief for the North American Geophysical Co., 636 Bankers Mortgage Bldg., Houston, Texas.

JOHN H. CROWELL has been advanced to the rank of Lieutenant Commander in the USNR, effective in November, 1944. Still better news came on the 10th of that month, when JOHN H. CROWELL, JR., was born. Friends will be glad to hear that RUTH and the baby are getting along excellently.

M. P. JONES has returned from Houston to Dallas, Texas, where he has been named Vice-President of the Garrett Exploration Co., 1423 Republic Bank Bldg., in that city. His residence address is 4512 N. Versailles, Dallas 5.

FRANCIS A. ROBERTS, of the Carter Oil Co., has returned from Moose Jaw, Sask., Canada, to the United States. His current mailing address is P.O. Box 294, Jonesboro, La.

W. W. BUTLER has left the Gulf Res. and Dev. Co. to accept a position as Party Chief for the Superior Oil Co. His mailing address is P.O. Box 102, Alva, Okla.

JOHN A. LESTER, of the Magnolia Pet. Co., has been transferred from Dallas, Texas, to Houston. He may be reached through P.O. Box 111, Houston 1.

CECIL E. REEL is now serving as Seismologist with the Superior Oil Co. His address is 2605 Avenida Escuela, Bakersfield, Calif.

J. EUGENE STONES, also with Superior, has advised the Society of his transfer from Seminole, Texas, to Weatherford, Okla., where his mailing address is P.O. Box 310, in care of the company.

DR. SIDON HARRIS, former North Texas-New Mexico Division Seismograph Supervisor for the Stanolind Oil and Gas Co., recently resigned to organize Southern Exploration Service, with offices in the Sinclair Bldg., Ft. Worth, Texas. Dr. Harris, prior to joining the staff of the Stanolind Oil and Gas Co. ten years ago, was associated with Humble for a year, and also served on the faculties of Rice Institute and the University of Texas in the course of his graduate work. His Ph.D. in Physics was received at the latter school.

R. M. BRADLEY, of the Cities Service Oil Co., has been transferred from Bartlesville, Oklahoma, to 1440 Mellie Esperson Bldg., Houston 2, Texas.

LT. NEAL HARDIN, JR., when last heard from, was stationed with the 6th Transport Squadron, 2nd F. G., A. T. C., Wilmington, Delaware.

MAURICE SKLAR, of the Shell Oil Co., Inc., has been transferred from Caro, Michigan, to Rosenberg, Texas, where he may be reached in care of General Delivery.

J. CARR has been transferred from the Shell Co. of Australia to the Shell Co. of Egypt, Cairo, Egypt.

A. B. HAMIL is District Supervisor for the National Geophysical Co., Inc., with offices at 1404 Tower Pet. Bldg., Dallas 1, Texas.

L. J. NEUMAN is President of the L. J. Neuman Co., with offices at 943 Mellie Esperson Bldg. and the laboratory on Pecan Road, Houston, Texas.

LT. A. B. MANNING should be addressed at 1138 Albion, Denver 7, Colo.

FRANK F. LEHMAN is Aviation Electrician at U. S. Naval Air Station #720. His mailing address is P.O. Box 1413, Cristobal, Canal Zone.

J. BYRON JONES is associated with the Geophysical Exploration Co., 130 East Fifth Ave., Denver 9, Colo.

MAJOR JOHN M. GOLDEN may be addressed at the Combined Maintenance Shops, Camp Van Dorn, Miss.

PETER JACOBSEN, JR., of the Carter Oil Co., has been transferred from Ft. Morgan, Colo., to Worland, Wyoming, where his postal address is Box 43.

HOWARD L. COBB, of the Atlantic Refg. Co., may be addressed at 1624 Irwin and Keasler Bldg., Dallas 1, Texas.

Public announcement was made September 1 of the dissolution of the National Geophysical Co. The National Geophysical Co., Inc., has been formed to carry on the geophysical business of the dissolved partnership, while drilling activities will be handled by the National Geophysical Drilling Co. Offices remain in the Tower Petroleum Bldg.

DAVID M. WEBER has returned to the States from South America and may be addressed at P.O. Box 352, Laurel, Miss.

R. E. MCMILLEN entered foreign work with the Seismograph Service Corp. early in July, 1944. He should be addressed in care of the Seismograph Service Corp. of Delaware, Aptdo. 1488, Caracas, Venezuela, S. A.

GERALD A. BURTON has moved from Casper to New Castle, Wyoming, where his postal address is Box 730.

LT. ELLIOTT SWEET has been transferred from the Boston Magnetic Ranges to Long Beach 2, Calif. His local address is 405 West 3rd St.

PHILLIP H. MINTZ has left Independent Exploration to accept a position as Seismograph Coordinator for the Venezuelan Atlantic Refg. Co., Caracas, Venezuela, S. A.

Upon receipt of his last advice, GEORGE B. SOMERS was temporarily located in Houston, Texas, at 4384 Wheeler Ave.

E. V. MCCOLLUM of E. V. McCollum and Company spoke before the Tulsa Geological Society November 20, 1944, on the subject, "The Interpretation of Gravity Anomalies."

SHERWIN F. KELLY has recently returned from South America, where he has been engaged in professional work.

On December 11 R. E. FEARON gave a demonstration lecture before the Tulsa section of the AIME entitled "Some Interesting Aspects of the Physics of Radioactivity Well Logging." In addition to reviewing the basic physical principles of radioactivity, Mr. Fearon used radiation detectors and gamma ray sources provided by Well Surveys, Inc., to demonstrate the rectilinear propagation, inverse square attenuation, absorption, and scattering properties of gamma rays.

JOHN F. ANDERSON, formerly with the Sun Oil Company at Beaumont, Texas, as Seismograph Supervisor, has become associated with the GEOPHYSICAL ENGINEERING COMPANY as Seismograph Supervisor, with offices at 410 Beacon Bldg., P.O. Box 2687, Tulsa, Oklahoma.

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912 AND MARCH 3, 1933

of GEOPHYSICS, published quarterly at Menasha, Wisconsin, for January, 1945

State of Arkansas }
County of Union } ss.

Before me, a Notary Public in and for the State and county aforesaid, personally appeared J. F. Gallie, who having been duly sworn according to law, deposes and says that he is the business manager of GEOPHYSICS, and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business managers are: Publisher, George Banta Publishing Company, Menasha, Wisconsin; Editor, Dr. Joseph A. Sharpe, P. O. Box 501, Tulsa 2, Oklahoma; Managing Editor, Dr. Joseph A. Sharpe, P. O. Box 501, Tulsa 2, Oklahoma; Business Manager, J. F. Gallie, P. O. Box 410, El Dorado, Arkansas.

2. That the owner is: Society of Exploration Geophysicists, P. O. Box 410, El Dorado, Arkansas; W. M. Rust, Jr., President, P. O. Box 2180, Houston 1, Texas; Henry C. Cortes, Vice-President, P. O. Box 900, Dallas 1, Texas; R. D. Wyckoff, Past President, P. O. Box 2038, Pittsburgh 30, Pa.; W. Harlan Taylor, Secretary-Treasurer, 1449 Mellie Esperson Bldg., Houston 2, Texas; Dr. Joseph A. Sharpe, Editor, P. O. Box 501, Tulsa 2, Oklahoma.

3. That the known bondholders, mortgagees, and other security holders owning or holding 1 per cent or more of total amount of bonds, mortgages, or other securities are: None.

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5. That the average number of copies of each issue of this publication sold or distributed, through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is not required. (This information is required from daily publications only.)

J. F. GALLIE (Signed)

Sworn to and subscribed before me this 2nd day of October 1944.

[SEAL] JESSIE RUTH BENTON (Signed)

(My commission expires June 8, 1947.)

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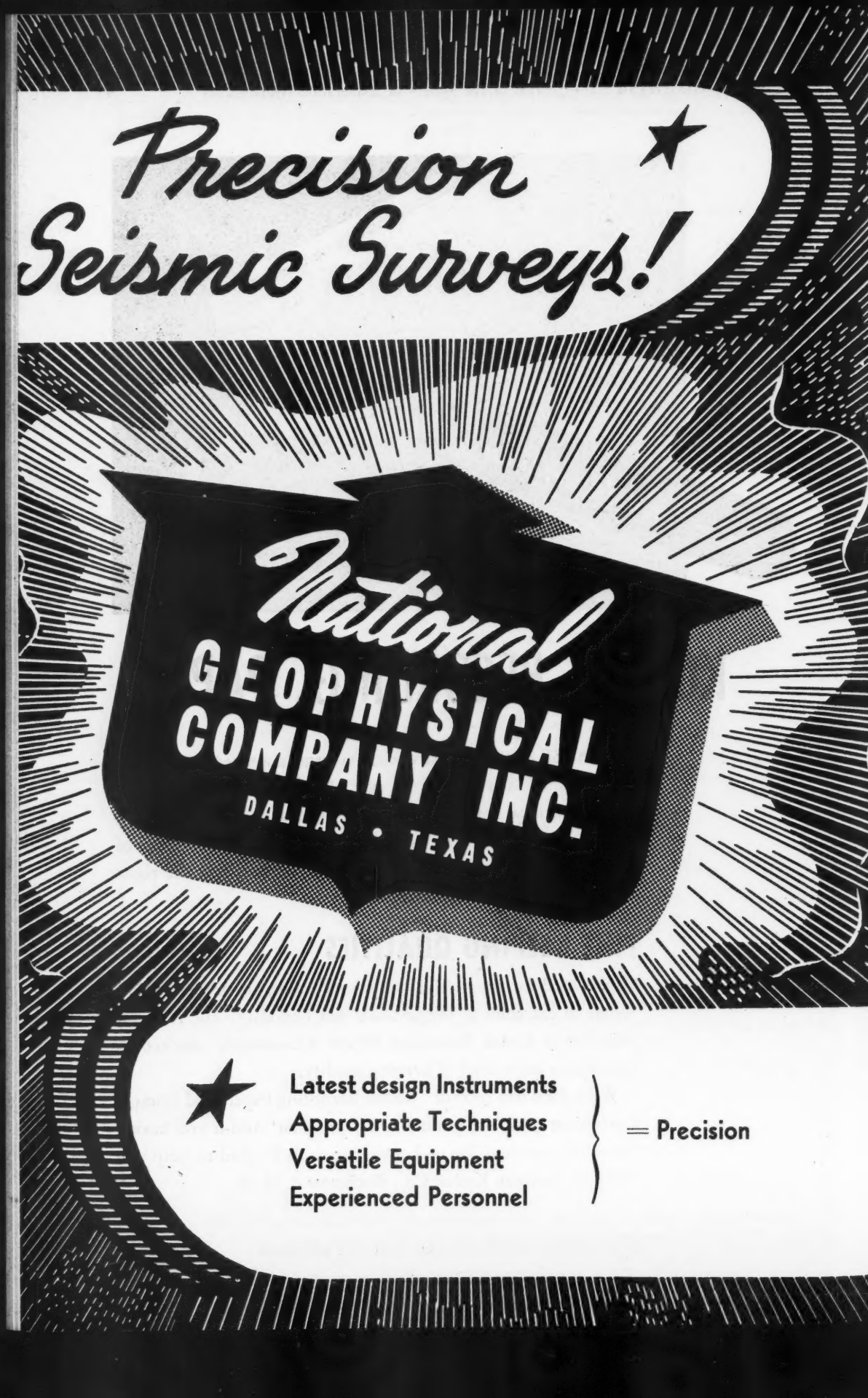
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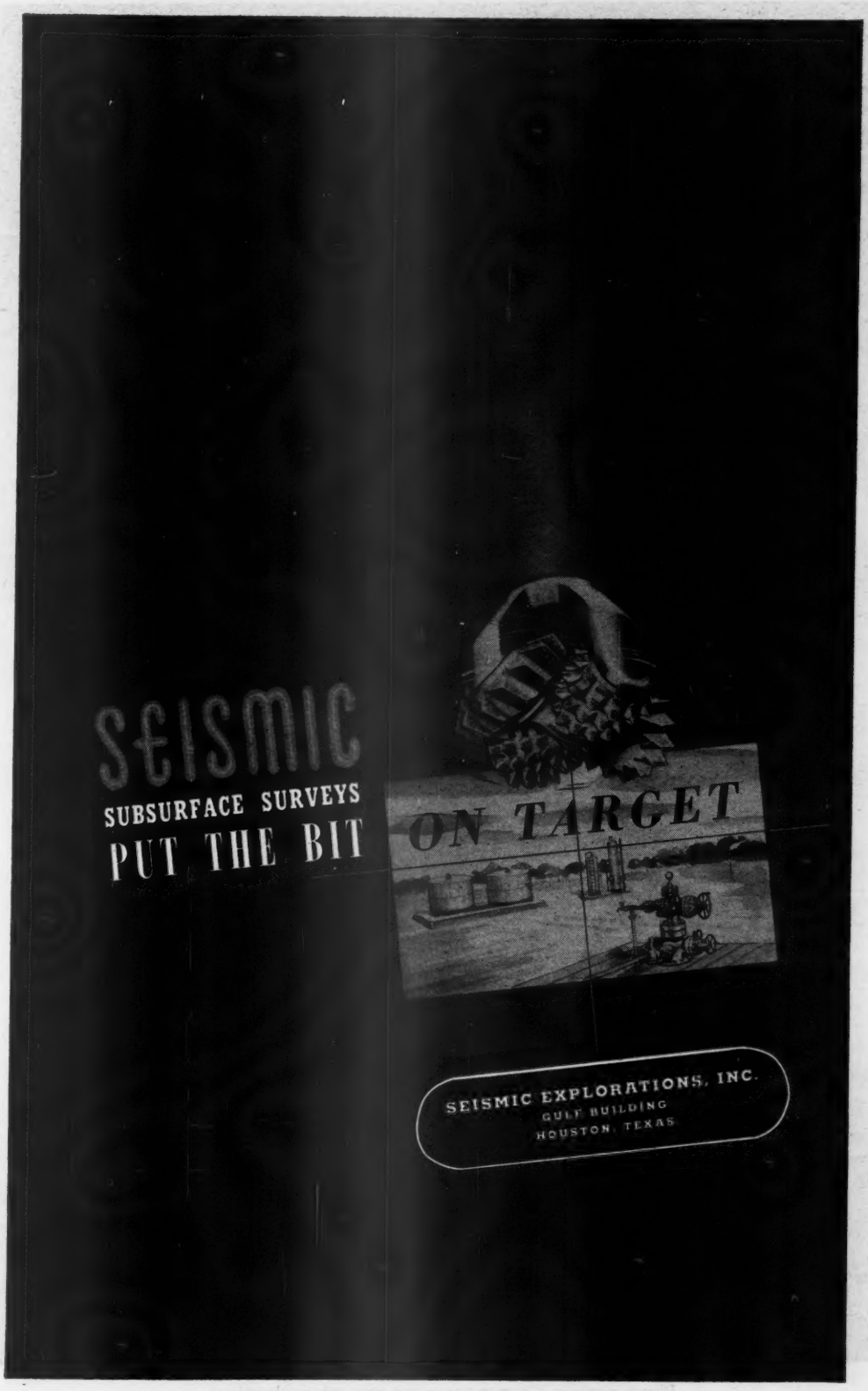
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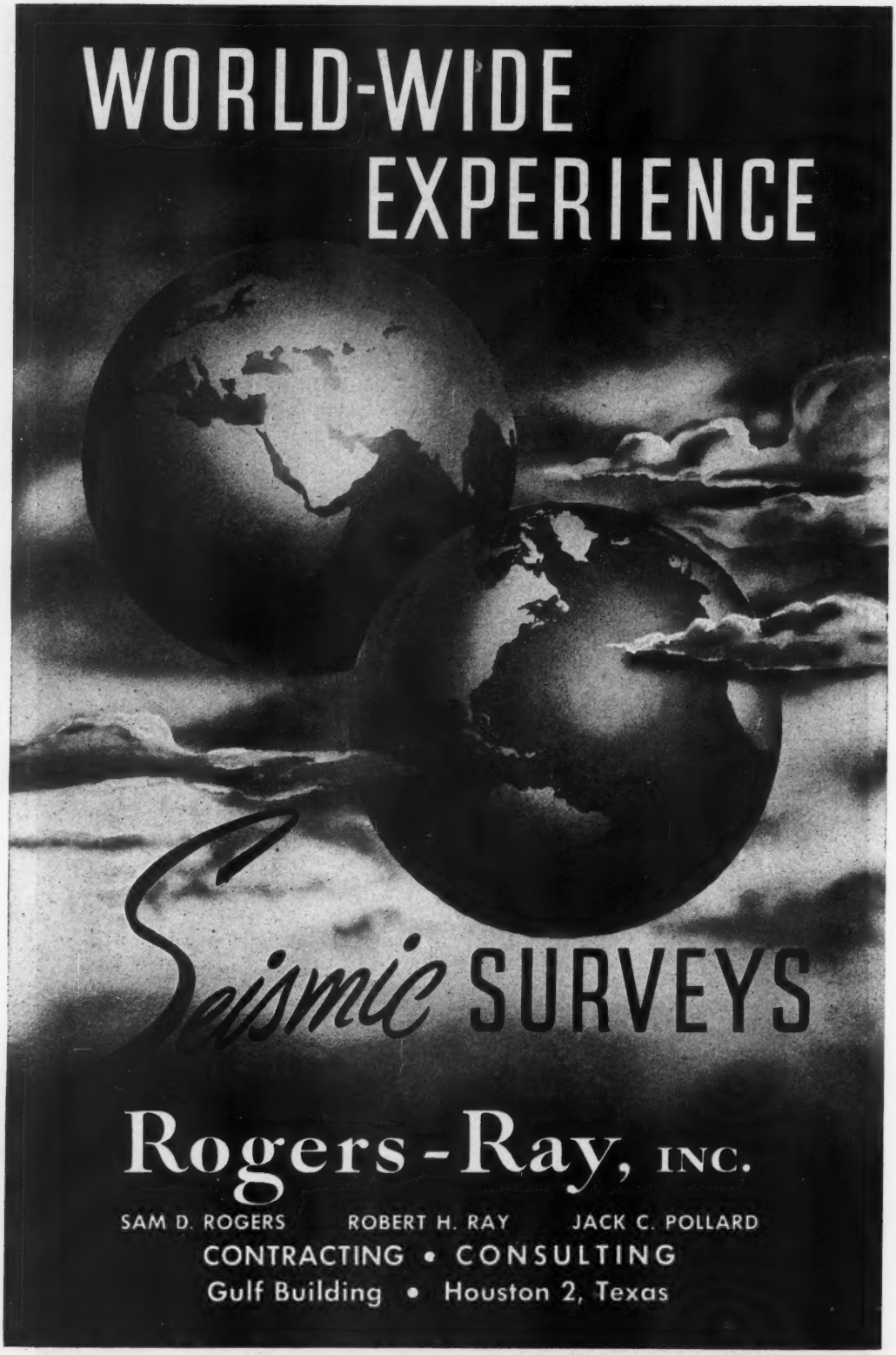
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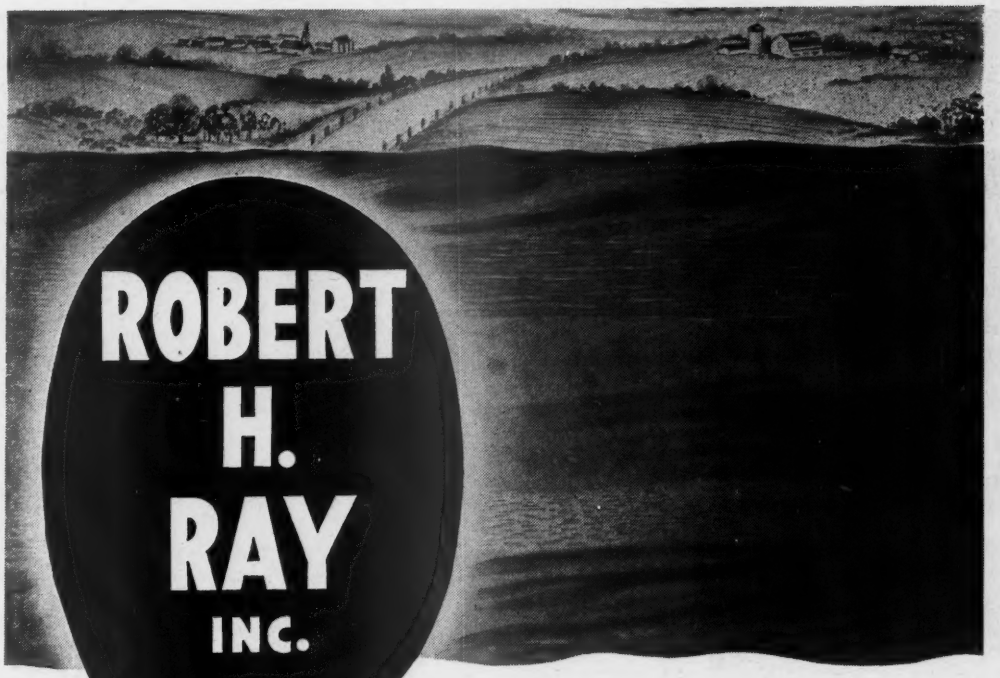

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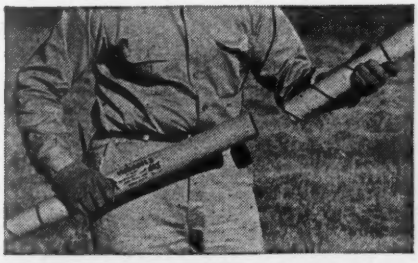

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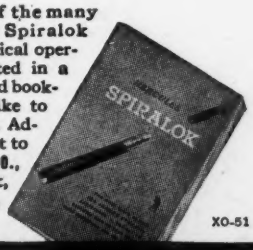

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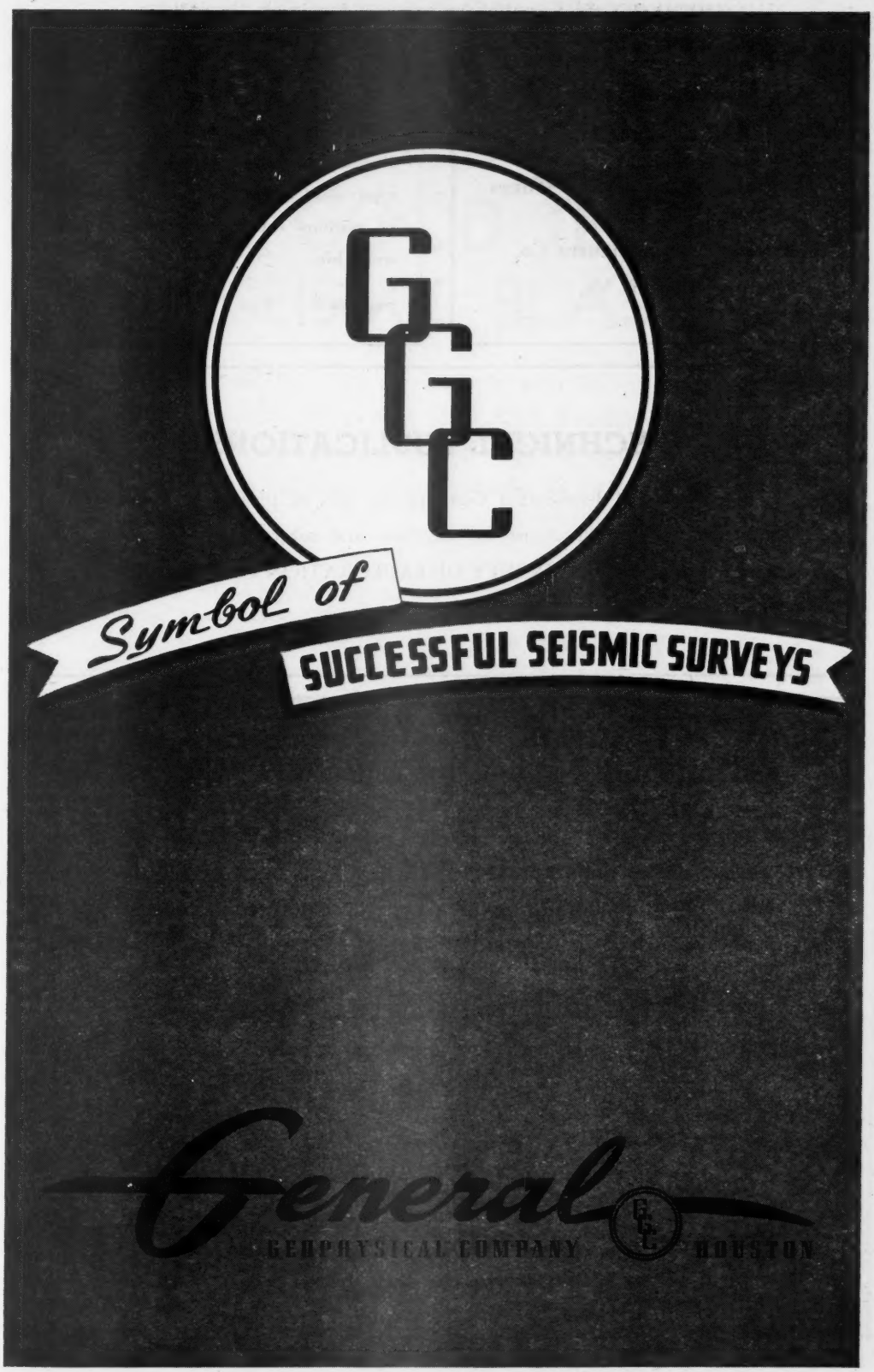
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Way back in 1930 we ran our first commercial survey, using the magnetic technique we had developed during the preceding four years of intensive research. The survey was made for a prominent and successful oil operator, for whom we have continued to work at intervals ever since. A few weeks ago this same client again asked us to make a survey for his account, and his request prompted us to see how many other old-time clients were using our service.

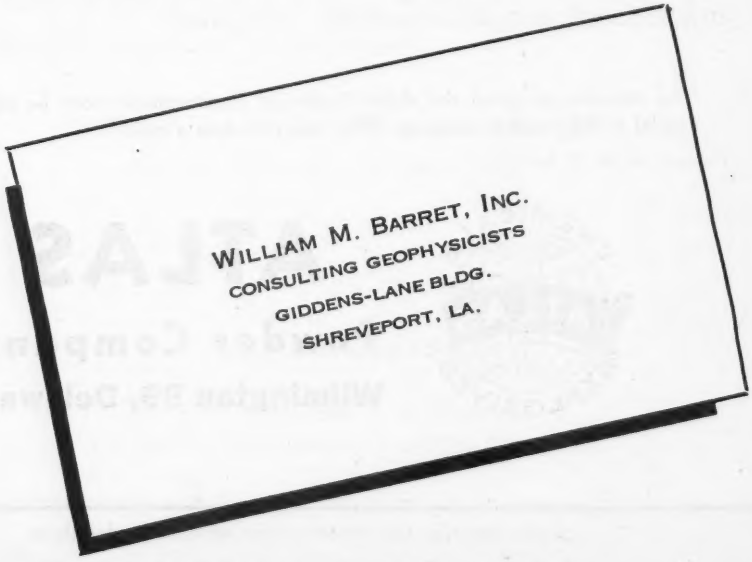
Surveys were in progress for two clients who first retained us in 1931; for another who initially used our service in 1932; for two other clients whose accounts we obtained in 1934; for another whom we first served in 1937, and for another who used our service for the first time in 1941. We had just completed a survey for still another client whose first survey was conducted in 1932. We found that:

These clients' combined experience with our service totaled 80 years.

Surveys were also in progress for a sprinkling of newcomers: one whom we first served in June, 1944; another in September, 1944, and we were preparing to start work for another client who also retained us first in September, 1944.

Our investigation showed that six new clients had been added to our list during the preceding 12 months of restricted wartime service: three major oil companies, one large independent company, and two independent operators.

By keeping our old clients, and constantly adding new clients, we are bringing to more and more people the marked advantages that go with Barret Magnetic Surveys.



SEISMIC REFLECTION

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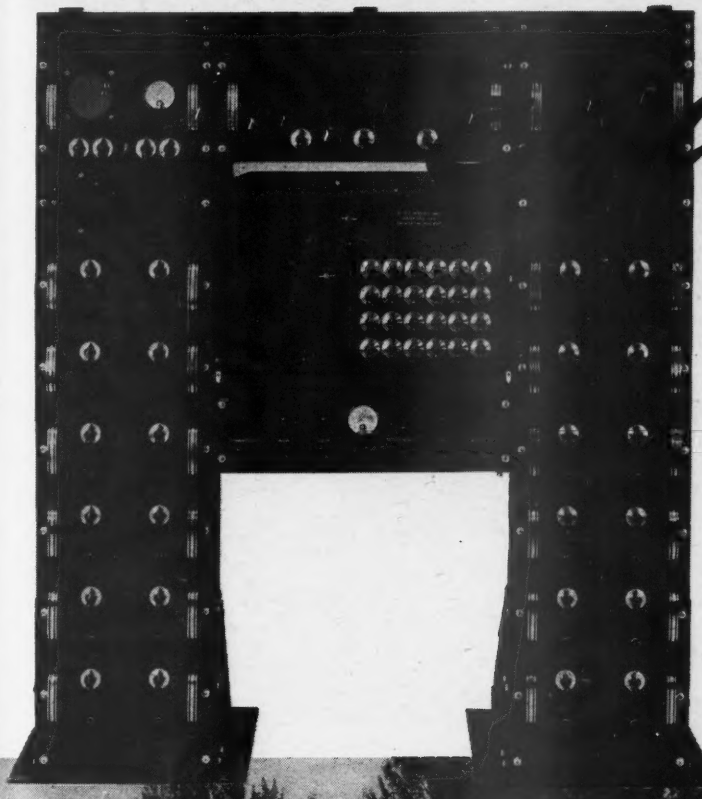

Equipment for seismic reflection shooting has to be ruggedly constructed to assure reliable and continuous operation in all types of terrain. Heiland Reflection Equipment is quantity produced to quality standards. Much of it has been in service so long that its year after year reliability has come to be universally accepted in the U.S. and abroad.

HEILAND RESEARCH CORPORATION

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BAROID WELL LOGGING SERVICE provides a successful method of determining the presence or absence of oil or gas in the various formations encountered while drilling, and of logging the depths and approximate thicknesses of such formations. The method is simple and also gives the operator additional information which heretofore has never been available and which enables him to drill a well more intelligently and with greater freedom from drilling difficulties.

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